Effect of the Leveling Conditions on Residual Stress Evolution of Hot Rolled High Strength Steels for Cold Forming

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Abstract. In order to investigate the effect of leveling conditions on residual stress evolution during the leveling process of hot rolled high strength steels, the in-plane residual stresses of sheet processed under controlled conditions at skin-pass mill and levelers were measured by cutting method. The residual stress was localized near the edge of sheet. As the thickness of sheet was increased, the residual stress occurred region was expanded. The magnitude of residual stress within the sheet was reduced as increasing the deformation occurred during the leveling process. But the residual stress itself was not removed completely. The magnitude of camber occurred at cut plate was able to be predicted by the residual stress distribution. A numerical algorithm was developed for analysing the effect of leveling conditions on residual stress. It was able to implement the effect of plastic deformation in leveling, tension, work roll bending, and initial state of sheet (residual stress and curl distribution). The validity of simulated results was verified from comparison with the experimentally measured residual stress and curl in a sheet.

1. Introduction

Hot rolled high strength steels are used for structural parts of automobiles and frames for commercial vehicles. And the hot rolled steels are, generally, slitted to small width coils for continuous press forming or processed in cut-to-length lines to sheet and scissored into designed shape (dimension) by plasma, laser, etc.

In order to ensure high strength properties for these steels, special ingredients and production process are incorporated. And the process inevitably lead to length and width directional non-uniformity in temperature history. Due to the unevenness in temperature, large amount of residual stresses are generated in the sheet. If large amount of residual stress have been generated in the hot rolled steels, during the cutting of hot rolled steels by slitter or plasma, there are high probability of shape defects occurrence such as curl and camber in cutted sheets. Due to these shape defects, the further processing of material becomes very difficult. Therefore, residual stress minimization in hot rolled coils is very important in real manufacturing field [1].

Residual stress along thickness direction is related with curl or L-bow of sheet and residual stress along width direction affects camber of shitted sheet. There were several studies on the evolution of residual stress along thickness direction in the leveling process such as Matoba [2] and Kano [3] but a few studies were found on residual stress along width direction. Maeda [4] reported an algorithm for analyzing width directional residual stress evolution during roller leveling. Maeda [4] treated residual stress as partial tension and the evolution of the partial tension during leveling process was consider under the basic condition that sum of all residual stress along width direction shoube be zero.
In order to investigate the evolution of residual stress during the processing of hot rolled coils, specimens at several major processing steps were obtained and residual stress distributions in the sheet were experimentally measured. From the measured stress distributions, leveling conditions that were suitable for reducing residual stresses were studied. The amount of camber after cutting was also predicted from residual stress distribution. In order to investigate the optimum leveling conditions for hot rolled coils for reducing residual stress, an algorithm for simulating leveling process was developed. This algorithm incorporates tension in the processing lines and the effect of work roll bending deformation in order to expand the method proposed by Maeda [4] for predicting residual stress evolutions during roller and tension leveling.

2. Residual stress evolution during leveling process

2.1. Measurement of residual stress in hot rolled sheet

Strain gage used for residual stress measurement is general purpose for steels and its gage length is 5mm. Sheets for residual stress measurement are obtained as full width sheet with 500mm length. Strain gages are attached upper and lower surface of sheet shown in Figure 1. After strain gage attachment, initial strain values are measured and the sheets are cut along cutting lines shown in Figure 1 by water-jet cutting machine shown in Figure 2. Residual stress distributions were obtained by using the measured strain values after cutting and before cutting for each gage. In order to extract bending strain, the upper and lower surface strains were averaged for in-plane residual stress measurement.

![Figure 1 Strain gage attached positions and cutting lines.](image1)

![Figure 2 Strain gage preparation, cutting by water jet.](image2)

2.2. Measurement of residual stress in hot rolled sheet

2.2.1. Residual stress evolution of 3.2t Hot Rolled Steel. Tested sheets (3.2mm thickness and 1231mm width high strength steels, its tensile strength is 800MPa) were obtained after skin pass rolling, rough leveling and finish leveling process. The thickness reduction in skin pass rolling is 0.5% at room temperature. The ratio of plastically deformed region to thickness is called plastic fraction and it is used...
for representing roller leveling conditions. The values of plastic fractions in rough and finish levelers were 58% and 72% respectively. The curvature of achieved sheet before water-jet cutting and after water-jet cutting are shown in Figure 3. After skin pass rolling, relatively large curvature deviations are appeared in a sheet but after roller leveling the large deviations in curvature are almost removed and small deviations in curvature at edge are still shown. But the small width deviations at edge are reduced by applying additional leveling deformation as shown in Figure 3.

![Curvature of sheet before cutting](image)

(a) Curvature of sheet before cutting

![Curvatures of cut sheet](image)

(b) Curvatures of cut sheet

**Figure 3 Curvature distributions in 3.2t plate after SPM and roller leveling.**

Residual stress distributions after skin pass rolling, rough and finish leveling are shown in Figure 4. After skin pass rolling the residual stress at edge is compressive but it changed to tensile about 60mm inner position from both edge of sheet. The residual stresses at sheet edge are distributed about 90mm width and length directional in plane residual stress in the inner part of sheet are very small. The camber distribution of cutted sheets measured are shown in Figure 5. The camber direction and magnitude are consistent with the residual stress distributions.

![Residual stress distribution in 3.2t sheets](image)

**Figure 4 Residual stress distribution in 3.2t sheets.**
As shown in Figure 4 and Figure 5, the magnitude and gradient of residual stress in hot rolled sheets are able to be reduced by applying more leveling deformations to the sheet by leveler. This trends in residual stress evolution by roller leveling are the same as general principles of roller leveling effect.

2.2.2. Residual stress evolution of 6.0t Hot Rolled Steel. The residual stresses of high strength hot rolled steels with 6mm thickness and 500mm length are measured and analysed in order to study the evolution of residual stress during leveling process. The thickness reduction in skin pass rolling is 0.5% at room temperature. The plastic fraction applied in rough and finish leveling are 75% and 78% respectively. The curvature distribution in cutted sheets are shown in Figure 6. Curvature deviations in a sheet are reduced by roller leveling and the deviations of curvature in a sheet are effectively reduced by increasing leveling deformation. But the deviations in curvature are still remained in edge region after leveling. And the width of curvature deviation region is about 120mm from edge of sheet. The width of non-uniform curvature in roller levelled 3.2mm thickness sheet was 90mm as in Figure 3 and this width is smaller than 6.0mm thickness sheets.

![Figure 5 Camber of cut sheet in 3.2t plate.](image1)

![Figure 6 Curvatures of cut sheet in 6.0t plate.](image2)

![Figure 7 Residual stress distribution in 6.0t sheets.](image3)
Residual stress distributions of sheet after skin pass rolling and roller leveling are shown in Figure 7. Large gradient in residual stress distributions are reduced after roller leveling and the reduction effects are greater than 3.2t sheet. This may be due to the larger plastic fraction applied to 6.0t sheet leveling case than 3.2t sheet leveling case. As the same as curvature deviations in the edge, width of residual stress occurred regions in 6.0mm thickness sheet (150mm) are wider than that of 3.2mm thickness sheets (90mm).

3. Relation between residual stress and camber after cutting

3.1. Computing camber amount from residual stress distribution

In order to utilize the measured residual stress distribution for computing camber after cutting, the relation between residual stress and camber after cutting is derived. An example of typical cutting process (under-water plasma cutting) is shown in Figure 8. If the residual stress distribution is assumed as quadratic equations, the camber amount is able to be computed by using cutting width, length and residual stress level [1]. If the stress distributions are not quadratic form as in Figure 4 and Figure 7, camber is not computed by simple equation. In these cases, the residual stress distributions are able to be treated numerically for computing moment in the cutted sheet and simple relation between moment and curvature [5] are applicable in camber computation as in Figure 9. Cambers in cutted plate are proportional to moment computed from in-plane residual stress, square of cutting length and it is in inverse proportion to the cube of cutted width.

![Figure 8 Under-water plasma cutting 468mm width from 8t x 1418w x 12135L leveled sheet.](image)

![Figure 9 Camber of cut plate from residual stress.](image)

3.2. Comparison between computed camber from residual stress distribution and measured camber

The residual stress distribution of properly roller levelled sheet (8mm thickness, 1418mm width, 800MPa tensile strength grade sheet) and computed camber for three 468mm width and 12m length sheets are shown in Figure 10. In real under-water plasma cutting process, the camber of sheets (468mm × 12m) at WS and DS are about -2mm and there is zero camber in the center sheet. Computed cambers at WS and DS are -2.4mm and -1.4mm respectively. By considering the difficulty in camber measurement, the computed and measured cambers are able to be treated as almost the same value.

Residual stresses in the sheet leveled at improper condition during finish leveling are shown in Figure 11. Residual stresses in the center part of sheet are non-symmetry between WS and DS. The residual stress distribution of sheet before finish leveling (after leveling in rough leveler) was already checked.
and it was found that the stress distribution was symmetric between WS and DS in the center and edge region. The computed and measured camber of sheet with 468mm width and 12mm length sheet also shown in Figure 11. The computed camber of WS sheet is 8.5mm but the measured value is about 10mm. The difference between computed and measured camber is about 17%. Camber occurred at center and DS side sheet is 1mm and 3mm and the computed cambers are 1.3mm and 3.9mm, respectively. Allowable camber for the 12mm length sheet after cutting is less than 6mm. Therefore the computed cambers from residual stresses are able to be applied to predict real camber values after cutting to small width sheet.

![Figure 10 Stress in properly leveled sheet.](image)

**Figure 10 Stress in properly leveled sheet.**

**Figure 11 Stress in improperly leveled sheet.**

4. **Effect of Leveling Conditions on Residual Stress**

4.1. **Characteristics of Leveling Process**

Leveling is a shape correction and residual stress reduction process by repeated bending-unbending under small tension through multiple number of work rolls. There are two kinds of process called tension leveling and roller leveling. About 1/3 of yield stress is applied as tension during leveling, the process is called tension leveling. And in the case of roller leveling, there is zero tension or very small tension for sheet travel only. For reducing (in plane) residual stress distributed along width of sheet, tension leveler is more effective process than roller leveler. This is because plastic deformation occurred all of the section of sheet in tension leveler, but the plastic deformation in roller leveler occurred a portion of the thickness. In this study, the effect of tension and roller leveler conditions on the in-plane residual stress distribution are analyzed by using developed numerical algorithm.

4.2. **Analysis of Leveling Deformation**

4.2.1. **Deformation analysis of bending-unbending under tension.** Leveling process is able to be considered as repeated bending-unbending under tension. In the case of tension levelers large tension is applied during the deformation but there is almost zero tension in roller leveling. Deformation analysis techniques on bending under tension [6, 7] were already reported and external tension was included in the algorithm for residual stress evolution during leveling that was proposed by Maeda [4] are applied in this study.

4.2.2. **Analysis of Residual Stress Change during Leveling.** During the leveling process, applied tension and the residual stress distributed in the sheet are added and affects in the leveling deformations. Therefore, larger tensile residual stress regions elongated more than the smaller tensile stress parts or compressive stress parts. In compressive residual stress parts, if the applied tension for leveling is almost zero, the length is able to be reduced a little. Due to the elongation adjustment by combined effect of tension and residual stress, distributions of residual stress are modified and the magnitude of residual stress is reduced. However non-uniform deformations, due to the work roll bending or other causes, are applied during the leveling process, the residual stress distributions in the sheet are able to be increased...
after leveling. In this research, not only apply additional tension in leveling process but also the effect of non-uniform bending deformation due to work roll deformation on residual stress in the sheet are considered. And the sum of final residual stress after leveling and unloading tension was treated as zero by spring back algorithm incorporated in the analysis.

Length directional (x-axis) average residual stress at each width position (y-axis) in the sheet is able to be obtained by averaging stress along thickness as like \[ \sigma_{out} (y) = \sum_{i=1}^{n} \sigma_{i}(z) \cdot dz / t \]. The strain in thickness center position (\( \varepsilon_{c} \)) is able to be computed at each slit by considering stress and tension equilibrium at bending-unbending under tension process [7]. Dividing the sheet in width direction (y-axis) as in Figure 12, average residual stress change during gradual leveling process is obtained as follows. The force related with deformation of i-th element is shown in Figure 13.

\[ \Delta y : \text{Slit width} \]
\[ < d_{c} > : \text{Average } d_{c} \text{ along width of plate} \]
\[ \Delta l(k) : \text{length of element} \]

By considering deformations, stress and equilibrium conditions, residual stress change by leveling in slit model is obtained as in equation (1). The \( f \) in equation (1) is used as an empirical constants for considering both elastic and plastic deformation in bending. The \( f \) value is selected as 1/6.5 by considering elastic modulus, plastic modulus and typical plastic fraction in leveling as 85%.

\[
\begin{align*}
\sigma_{out}^{(i)} &= -f \cdot E \left( d_{c}^{(i)} - \frac{\sum d_{c}^{(i)}}{L} \right) + f \cdot G \cdot \left( \frac{d_{c}^{(i+1)} - d_{c}^{(i)}}{\Delta y} - \frac{d_{c}^{(i-1)} - d_{c}^{(i)}}{\Delta y} \right), \Delta l^{(k)}
\end{align*}
\]

4.2.3. Effect of work roll deflection on residual stress. 8t \( \times \) 1430w and 800MPa yield strength sheet was considered. The width directional divisions are 10 for half width of sheet. Roller leveling condition is adjusted as 85% plastic fraction at entrance of leveler. For zero residual stress sheet and the leveler work roll (length=2670mm) deflects as quadratic shape, the computed curl and residual stress distribution after leveling are shown in Figure 14.
As increasing work roll deflection, non-uniform curl and residual stress are increased. Therefore, in leveling, backup roll adjustments for suppressing work roll bending (deflection) are essential.

4.2.4. Measured and computed residual stress after leveling. The tested residual stress changes during leveling (87% plastic fraction) are shown in Figure 15. And the computed residual stress after leveling by the developed algorithm are shown in Figure 16. By comparison with the measured and computed results, it is able to be found that about 1~2mm work roll deflection was occurred during leveling.

5. Conclusion
In order to investigate the effect of leveling conditions on residual stress evolution during the production process of hot rolled high strength steels, the in-plane residual stress of sheets after skin-pass rolling and rough and finish leveling were measured. The residual stress was localized near the both edge of sheet. As the thickness of sheet is increased, residual stress concentrated region was expanded. The magnitude of residual stress within the sheet was reduced as increasing the deformation occurred during the leveling. But the residual stress itself was not removed completely by leveling. The magnitude of camber occurred at cut plate was computed exactly by the measured residual stress distribution. A numerical algorithm was developed for analysing the effect of leveling conditions on residual stress. It was able to implement the effect of plastic deformation, tension, work roll bending and initial state of sheet. The validity of computed results were verified by comparison with the experimentally measured residual stress in a sheet.

From this results, it was found that magnitude of residual stress is able to be controlled by adjusting leveling conditions and the effects of plastic deformation, line tension and effect of work roll bending deformation on residual stress are able to be properly predicted. Therefore camber problems in hot rolled coils could be solved by applying this results.

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