Mechanism of End Deformation after Cutting of Light Gauge Channel Steel Formed by Roll Forming

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Light gauge channel steel is fabricated from a steel sheet by roll forming. Cut end deformation of the channel steel was investigated by experimentation and three-dimensional finite-element simulation. During roll-forming, concave, convex, and reverse bending deformations on a flange occur and cause bending lines to diverge from the point of contact between the top roll and the flange corner. The reverse bending deformation is caused by a bending moment and a twisting moment. These moments remain on the flange. When the channel steel is cut, the release of the bending moment results in opening at both the top end and the tail end. Then, the release of the twisting moment makes the flange close at the top end and open at the tail end. Deformations at the tail end open widely with the overlap of the two moments.


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1. Introduction

When a product produced by cold roll forming is cut into lengths, deformation near the cut section occurs under the release of residual stresses. This deformation is generally designated as cut end deformation. If the deformation is large at the cut edge, then the product size will be out of standard, rendering it unusable. Moreover, the cut end deformation makes joining together edges of the product or joining the edge of the product with other components difficult. Therefore, a process of amending the deformation edge is necessary. Straightening them one by one brings about poor production efficiency. Consequently, the development of a roll forming method that might prevent cut end deformation is desired.

Many papers have been published with respect to cut end deformation of channel steel. Kato et al.1) measured dimensions in cut sections of channel steel to clarify the tendency of closing deformation of the top end and opening deformation of the tail end. Additionally, they examined the relation between mechanical properties of the sheet metal and the cut end deformation. Mihara et al.2) conducted experiments on forming of U-shaped ribs, having found that inserting small-diameter inner rolls in the U-shaped cross-section at the last stand was effective to suppress end deformation. Conducting a series of forming experiments on the channel, hat, and C-channel steels, Ona et al.3) described that the bending moment and torsional moment which act by contact with rolls were the cause of cut end deformation. Some studies have been conducted in this way but the relation between bending deformation and residual stress in roll-formed channel remain uncertain.

To date, research on cut end deformation of square channel steel by roll forming has been reported by Nagamachi et al.4,5) The present report describes continuity of that research. It specifically examines cut end deformation of channel steel. First, finite element simulation of light gauge channel steel forming processing and cutting processing are done. Then, the calculation result and experimentally obtained result are compared. In addition, the relation between bending deformation of light gauge channel steel and residual stress are investigated, the mechanism of cut end deformation is discussed according to the calculated residual stress.

2. Experiment and Analysis

Figure 1 presents a schematic view of the forming process used for this study. A metal sheet is bent at the corner position by rolls No. 1–No. 6. The flange is formed in this process. The rolls and their dimensions are presented in Fig. 2. Table 1 presents mechanical properties of sheet metal derived from tensile tests.

The simulation process, depicted in Fig. 3, is explained as follows. First, simulation of the channel steel forming process
is performed. In an experiment, the bottom rolls are driven and the top rolls are non-driven. The metal sheet velocity is \( V_z = 24 \text{ mm/s} \). It is set at the longitudinal top end as a boundary condition in the simulation. At this time, the angular velocity of a roll is computed so that torque might become almost zero in the simulation. Coulomb friction is used for the friction between the metal sheet and roll. The friction coefficient is 0.12. The longitudinal length of the analysis domain is 750 mm, which is double the length of the interval of each roll-stand.

Then, cutting processes are simulated. The process is the following. (1) Select one cross section in the stationary deformation region in the forming process. (2) Transfer coordinates and stress-strain data in a longitudinal direction to generate a model that has uniform sectional shape in the longitudinal direction. (3) Remove boundary condition at both ends to allow deformation at the cutting section. (4) Determine the cut end deformation by displacement of nodes that produce a force imbalance. The analysis domain for FE analysis was cut by hexahedral elements with eight nodes. Numerous solid elements in the thickness direction are necessary to calculate the deformation of elastic recovery. However, it makes the computation time extremely large. We conduct a simulation with three layers in the thickness direction. It is the minimum number of layers that can reproduce the analysis of elastic recovery, as understood by examination of the previous report.4,5) The total number of elements was 35,000. FE simulation was conducted using a static implicit scheme applied to transient elasto-plastic analysis. A general-purpose code of DEFORM-3D Ver. 10.1 was used to perform calculations.

3. Results and Discussion

3.1 Relation between the forming condition and cut end deformation

Notation representing the cut channel steel shape is portrayed in Fig. 4. The pass direction was designated as the z direction and the cutting edge was \( z = 0 \text{ mm} \). We define \( w-l-t \) as a local coordinate system in which the \( w \)-direction denotes the width (transversal) direction, \( l \)-direction signifies the longitudinal direction, and \( t \)-direction stands for the thickness direction. Figure 5 shows the longitudinal distribution of the bent angle of cut channel steel. The bent angle in the cross section at \( z = 200 \text{ mm} \) is in a stationary region defined as \( \alpha_0 \). In addition, the bent angle at position of arbitrary \( z \) is defined as \( \alpha \). The absolute value of increment of bent angle \( \alpha - \alpha_0 \) is presented in Fig. 5. For \( \alpha - \alpha_0 \), the top end has closing deformation (\( \alpha - \alpha_0 \) is positive when \( z \)
values approach 0 from negative value), whereas the tail end has opening deformation \((\alpha - \alpha_0)\) is negative when \(z\) values approach 0 from positive value. Then \(\alpha_F\) and \(\alpha_B\) are defined respectively as the bent angle of the top end and the tail end. As depicted in Fig. 5, \(\alpha_F - \alpha_0\) is 1.1°, whereas \(\alpha_B - \alpha_0\) is \(-1.5°\). In other words, the opening angle at the tail end is larger than the closing angle at the top end. Those results resemble experimental results.

To support a detailed investigation, the cutting process simulation was conducted for channel steel formed by each forming process No. 1–No. 5. \(\alpha_F - \alpha_B\), which denotes the difference of bent angles of both cutting sections, is depicted in Fig. 6. The values \(\alpha_F - \alpha_B\) of processes No. 1 and No. 2 are considerably large.

### 3.2 Relation between bending deformation and residual stress

The occurrence of cut end deformation of product formed by roll forming is believed to result from shear deformations. They are in-plane shear stress in transversal-longitudinal direction and in-thickness shear stress in thickness-longitudinal direction. However, no research seems to provide a detailed explanation of the generation of in-plane shear deformation and the mechanism by which shear deformation causes cut end deformation. Therefore, the relation between stresses and bending deformation is examined in this research by the calculated residual shear stress and longitudinal stress. Figure 6 shows that large cut end deformation occurs at the early stages of channel steel forming. Consequently, the following discussion will specifically relate to the channel formed by No. 1 rolls. The distributions of transversal stress \(\sigma_w\), longitudinal stress \(\sigma_l\), shear stress in longitudinal-thickness (in-thickness) direction \(\tau_{lt}\) and shear stress in transversal-longitudinal (in-plane) direction \(\tau_{wl}\) are depicted in Fig. 7.

The horizontal axis, \(c/c_0\) represents the transversal position, where \(c/c_0 = 0\) is the center of web and \(c/c_0 = 1\) is the edge. The value of \(\tau_{lt}\) shown in Fig. 7 is almost 0. We again performed a simulation with six layers in the thickness direction. The \(\tau_{lt}\) value of the result provided an almost identical value with the three layers. Because the steel sheet used in this research is a thin sheet, bending deformation mainly occurs, with no shear deformation related to the thickness direction.

As portrayed in Fig. 7(b), in the wide domain of flange, the \(\sigma_l\) at the outer layer is tensile stress, whereas that at the inner layer is compressive stress. They are residual stresses. Similarly, Fig. 7(d) shows that the \(\tau_{wl}\) of the outer layer is in a reverse direction to that of the inner layer. They are residual shear stresses. Consequently, cut end deformation occurs by the release of both \(\sigma_l\) and \(\tau_{wl}\) residual stresses. The generation mechanism is discussed in section 3.3. The value of transversal stress \(\sigma_w\) in Fig. 7(a) is nearly zero because the flexural rigidity in a transversal direction is small and the springback in transversal direction occurs easily.
Residual stress on channel steel formed by rolls No. 2–No. 6 is similar to that formed by the No. 1 roll.\(^7\)

Residual stresses \(\sigma_i\) and \(\tau_{wl}\) depend strongly on the contact state of a flange with a roll and on the flange deformation state. In this session, the generation mechanism of residual stress is discussed by the contact with No. 1 rolls and plastic strain rate in the flange.

Figure 8 demonstrates the deformation state of channel steel being formed by No. 1 rolls and contact area with rolls. The dotted marks \(\circ\) and \(\bullet\) respectively show the points of contact between the top roll and bottom roll. The dashed line shows the longitudinal position of rotational center of rolls, and also shows the minimum position of the roll gap. Hereinafter, this “roll center” line will be abbreviated as “R.C.” Additional details of flange bending forming are explained as follows. First, the sheet metal makes contact with the bottom roll at position A. The bottom roll lifts it up. Then sheet metal will produce contacts with the top roll at the corner of position B. Next, the sheet metal will be bent in the transversal direction as the top roll presses it down at the corner of position B. Then sheet metal will produce contacts with the top roll at the corner of position C near R.C., the corner. When the sheet metal makes contact with the top roll at position C near R.C., the flange will rise by the designated angle. During this process, the flange surrounded by A–B–C will be bent along the curved surface of the bottom roll, where the sheet metal is bent convexly in a longitudinal direction.

Figure 9 demonstrates the distribution of plastic strain rate for inner and outer elements of channel steel being formed by No. 1 rolls. Figures 9(a), 9(b), and 9(c), respectively, show the transversal strain rate \(\dot{\varepsilon}^p_w / s^1\), longitudinal strain rate \(\dot{\varepsilon}^p_l / s^1\) and shear strain in the transversal longitudinal direction \(\dot{\gamma}^p_{wl} / s^1\). The upper diagrams show the inner layer, whereas the lower diagrams show the outer layer. As a matter of course, those absolute values are large in domain surrounded by A–B–C that had large deformation. At position B, the inner layer is \(\dot{\varepsilon}^p_w < 0\). The outer layer is \(\dot{\varepsilon}^p_0 > 0\), where deformation shows the bending concavely in the transversal direction. From position A to B, the inner layer is \(\dot{\varepsilon}^p_0 > 0\) and the outer layer is \(\dot{\varepsilon}^p_0 < 0\), where deformation shows the bending convexly in longitudinal direction because the flange follows the curve of the bottom roll, as already depicted in Fig. 8.

Next, we specifically examine the flange in the downstream domain from position R.C. At the position around D in the figure, both layer inner and outer are \(|\dot{\varepsilon}^p_0| > 0\), \(|\dot{\varepsilon}^p_w| > 0\) and \(|\dot{\gamma}^p_{wl}| > 0\). In other words, plastic deformation occurs around position D. At this position, the inner layer is \(\dot{\varepsilon}^p_0 < 0\), the outer layer is \(\dot{\varepsilon}^p_0 > 0\), the inner layer is \(\dot{\gamma}^p_{wl} > 0\) and the outer layer is \(\dot{\gamma}^p_{wl} < 0\). These signs (positive or negative) for \(\dot{\varepsilon}^p_0\) and \(\dot{\gamma}^p_{wl}\) of layers respectively coincide with the sign for \(\sigma_i\) and \(\tau_{wl}\) shown in Fig. 9(b) and 9(c). In conclusion, residual stresses occur in the same direction in which plastic deformation takes place in the downstream domain near the roll center.

We can estimate the bending deformation of the channel steel being formed by the No. 1 roll in consideration of \(\dot{\varepsilon}^p_w\) and \(\dot{\gamma}^p_{wl}\) presented in Fig. 9, in addition to the maximum principle strain rate and minimum principle stress rate calculated from simulations. Those illustrations are depicted in Fig. 10. The flange surrounded by A–B–C is bent along the curved surface of the bottom roll as depicted in Fig. 8 and Fig. 9. It is bent convexly on bending line c–b. This bend is plastic deformation. The curved flange is forced to become straight in the longitudinal direction in the downstream domain from position R.C. (near D). In other words, having
reverse bending. Because the corner of the downstream domain has already been bent with bending line b–e, the curved flange is bent reversely with the bending line b–d. Therefore, the flange is bent. It is bent reversely with each bending line radiating from the position B, which is the intersection of the corner line and the R.C. line.

We will specifically examine reverse bending near D and will discuss the generation of residual stress. We define the direction of reverse bending line b–d as the \( w' \) direction, normal direction of the \( w' \) direction in plane of flange as \( l \) direction. The thickness direction is defined as the \( l \) direction. Those are depicted in Fig. 10. Reverse bending with the bending line in \( w' \) direction occurs. Consequently, the strain rate in the \( l \) direction \( \varepsilon_{fl}^{0} \) is compression \( (\varepsilon_{fl}^{0} < 0) \) in the inner layer and tension \( (\varepsilon_{fl}^{0} > 0) \) in the outer layer. We consider a coordinate system based on the longitudinal direction (\( l \) direction). We transform \( \varepsilon_{fl}^{0} \) into components in the \( w-l-t \) coordinate system. Those are \( \varepsilon_{0}^{wl}, \varepsilon_{l}^{wl} \) and \( \varepsilon_{t}^{wl} \) as present in right panel of Fig. 10. If it does so, then \( \varepsilon_{0}^{wl} \) is compression \( (\varepsilon_{0}^{wl} < 0) \) in the inner layer, \( \varepsilon_{l}^{wl} \) is tension \( (\varepsilon_{l}^{wl} > 0) \) in the outer layer, \( \varepsilon_{t}^{wl} \) is plus \( (\varepsilon_{t}^{wl} > 0) \) in the inner layer and \( \varepsilon_{t}^{wl} \) is minus \( (\varepsilon_{t}^{wl} < 0) \) in the outer layer. As depicted in Fig. 10(b) and (c), \( \varepsilon_{0}^{wl} > 0 \) and \( \varepsilon_{l}^{wl} < 0 \) in the inner layer near D, whereas \( \varepsilon_{0}^{wl} > 0 \) and \( \varepsilon_{t}^{wl} < 0 \) in the outer layer near D. Each sign (positive or negative) corresponds with the sign in the right panel of Fig. 10. Furthermore, as portrayed in Figs. 7(b) and 7(d), each sign of \( \sigma_{l} \) and \( t_{wl} \) is a residual stress corresponding with the sign of \( \varepsilon_{0}^{wl}, \varepsilon_{l}^{wl}, \varepsilon_{t}^{wl} \) near D in Figs. 9(b) and 9(c).

We estimated the bending deformation for channel steel formed by No. 2–No. 6 rolls by observing the strain rate from results of simulations. The following result was confirmed. Similar with the No. 1 roll, the flange is bent. It is bent reversely with each bending line radiating from the position that is the intersection of the corner line and R.C. line.

### 3.3 Generation mechanism of cut end deformation

As depicted in Fig. 10, the flange surrounded by A–B–C will bend along the curved surface of the bottom roll, where the sheet metal is bent convexly in a longitudinal direction. It is bent reversely with bending line b–d. We discussed the relation between the reverse bending and the moment acts on the flange. We also clarified the cut end deformation mechanism.

Figure 11 shows a schematic illustration of reverse bending. To simplify the problem, we consider the curved thin sheet metal with uniform bending rate in \( l \) direction. We assume that the bending moment acts on the curved sheet metal and that the curved sheet is forced to become a flat sheet by reverse bending with bending line b–d along the \( w' \) direction. If a plane stress condition is assumed, then stress \( \sigma_{l} \) in the \( l \) direction is compression \( (\sigma_{l} < 0) \) in upper surface and tension \( (\sigma_{l} > 0) \) in the lower surface. Additionally, we define the bending moment around the \( w' \) axis as \( M_{l} \); the \( M_{l} \) per unit width is shown as presented below.

\[
M_{l} = \int \sigma_{l} l \, dt \tag{1}
\]

\( M_{l} \) is a “residual” moment because \( \sigma_{l} \) is “residual” stress. Here, the coordinate conversion of the moment is performed from the \( w'-l' \) coordinate system into the \( w-l \) coordinate system. When the angle of rotation from \( w'-l' \) to \( w-l \) is defined as \( \theta \), the bending moment and twisting moment are shown as presented below.

\[
\begin{align*}
M_{w} &= M_{w'} \cos^{2} \theta + M_{l} \sin^{2} \theta - M_{w'} \sin 2\theta \\
M_{h} &= M_{w'} \sin^{2} \theta + M_{l} \cos^{2} \theta + M_{w'} \sin 2\theta \\
M_{wl} &= \frac{M_{w} - M_{l}}{2} \sin 2\theta + M_{w'} \cos 2\theta \\
M_{lw} &= -M_{wl}
\end{align*}
\]  

Here, the \( M_{w}, M_{h}, \) and \( M_{l} \) are the bending moments around the \( l' \) axis, \( l \) axis, and \( w' \) axis respectively, whereas the \( M_{w'}. \)
\( M_w, M_l \) are the twisting moment around the \( w' \) axis, \( w \) axis, and \( l \) axis, respectively. As depicted in Fig. 11(a), by assuming \( M_w = 0 \) and \( M_l = 0 \), the eqs. (2) are shown as presented below.

\[
\begin{align*}
M_w &= M_f \sin^2 \theta \\
M_l &= M_f \cos^2 \theta \\
M_{wl} &= \frac{M_f}{2} \sin 2\theta \\
M_{lw} &= -M_{wl}
\end{align*}
\]

(3)

Figure 11(b) presents these moments schematically. In addition, the \( M_w, M_l \) and \( M_{wl} \) per unit width is presented below.\(^8\)

\[
\begin{align*}
M_w &= \int \sigma_w t \, dt \\
M_l &= \int \sigma_l t \, dt \\
M_{wl} &= \int \tau_{wl} t \, dt
\end{align*}
\]

(4)

In short, bending moments \((M_w, M_l)\) and twisting moments \((M_{wl}, M_{lw})\) remain in the flat sheet.

The cut end deformation is discussed by considering the flat plate as the channel steel flange. The moments remain on the flange. When those moments are released, these engender the occurrence of cut end deformation, as depicted in Fig. 12. We examine each of the releases of the bending moment and torsional moment. They are depicted respectively in Fig. 12(a) and 12(b). In this case, the bending moment \( M_w \) around the \( l \) axis is unrelated to the cut end deformation because the release of residual stress \( \sigma_w \) is attributable to deformation in springback.

In Fig. 12(a), both the top end and tail end have opening deformation by release of bending moment \( M_l \). In Fig. 12(b), the top end has closing deformation. The tail end has opening deformation by release of twisting moments \( M_{wl} \) and \( M_{lw} \). The quantity of opening deformation at the tail end with the overlap of the two moments is greater than the quantity of closing deformation at top end, which accords well with the result presented in Fig. 5. Ona et al.\(^3\) described that the factor of cut end deformation is the bending moment and twisting moment that arise by contact with a roll. This study clarified that the moments which arise by contact with a roll are not the factor. The sectional shape of the channel must be retained toward the downstream area. For this purpose, reverse bending occurs on downstream domain from position R.C. The bending moment and twisting moment which arise by the reverse bending are the factors of cut end deformation.

4. Conclusion

(1) Simulation of the forming process and the cutting process were done on light gauge channel steel. Deformation of the cutting edge, which was closing at the top end and opening at the tail end was reproduced by simulation. Greater cut end deformation occurs at the early stages of channel steel formation.

(2) The flange is bent along the curved surface of the bottom roll. Then it is bent reversely. This bending of both kinds occurs in each bending line radiating from the intersection of the corner line and minimum gap line of rolls. Reverse bending, which occurs on the downstream domain from the position of the roll center, results from the bending moment and twisting moment. These moments remain in the flange. They become residual stresses: longitudinal stress and shear stress in the transversal-longitudinal (in-plane) direction.

(3) By release of the residual bending moment, both the top end and tail end of the cutting edge have opening deformation. By the release of residual twisting moments, the top end has closing deformation and the tail end has opening deformation. The opening deformation at the tail end is large because of the overlap of the two deformations.

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