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

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- He is the First as well as the Last, the Manifest as well as the Hidden,and He has knowledge of everything-

(al-Hadid (Iron) verses 3).

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Abstract

This thesis presents on the end deformation after cutting of light gauge channel steel formed by roll forming. The hat shape channel steel is widely used as a sheet pile which is driven into the foundation for the deck plate of a building, roof material and sheathing or water stoppage, etc. This kind of channel steel is mainly fabricated by roll forming. When hat shape channel steel cut into specified length, the cutting mouth of the product will change by the release of residual stress. This change is generally called cut end deformation. If deformation at cutting mouth of the product is large, the size of a cutting mouth will become out of standard. This will result on joining failure when joining channel steel with other channel steel or channel steel with other components, since deformation arise to the mouth of the channel steel. Therefore, the process of amending the size of the mouth which cut end deformation occurs at front end and back end is needed. This will make production efficiency fall. Moreover, when carrying out flying cut, if a cutting mouth of product changes immediately after cutting, it will lead to cogs breakage. Development of the roll forming method which cut end deformation does not produce from the above is desired. Therefore, this thesis is focused to solve cut this problem by suggesting the improvement of fabrication of light gauge channel steel by roll forming.

In this research, cut end deformation of hat shape channel steel and its mechanism was investigated by three-dimensional finite element simulation. The simulation is conducted using by transient elastic-plastic analysis by a static implicit method. First, 6 tandem of rolls, No.1~No.6 are built and 4 size of lips, 0mm, 9mm,16mm and 23mm channel steel are formed by this rolls. Then, from

simulation results, relation between simulation result and experimental result is compared.

From the results, channel steel with lip having opening deformation at both front and back end. However, channel steel without lip having closing deformation at the front, and opening deformation at back end. During roll forming process, concave, convex and reverse bending deformation on flange take effect and make bending lines diverge from contact point between top roll and corner of flange. The reverse bending deformation is caused by bending moment and twisting moment. These moments remain on the flange. When channel steel is cut, release of the bending moment results on opening on both front end and back end. At that moment, release of twisting moment makes the flange closing at the front end and opening at the back end.

Inner rolls at the end of the finale tandem are proposed. Previously, by performing a finite element simulation of the cutting process and the roll-forming process of the channel steel, the residual shear stress in the inner layer are in different directions at the inner and outer layer which is the factor of the occurrence of cut end deformation which result in opening at the back end and closing at the tail end. In the experiments, the result shown that an inner side roll has an effect in cut end deformation, and drum type inner roll is more effective. For this reason, inserting inner rolls at the finale tandem was applied on channel steel and simulation on it was done. As a finishing process after fabrication of a product, the No.7 outer roll and No.8 inner roll were attached. Therefore, this chapter will verify the methode to eliminate cut end deformation by applying a small inner roll at finale tandem of the roll forming process. In this research, finite element method (FEM) is used and the mechanism of the cut end deformation by inserting inner roll will be discussed.

Keywords

roll forming, cut end deformation, light gauge channel, hat shape channel steel, residual stress, FE analysis

Contents

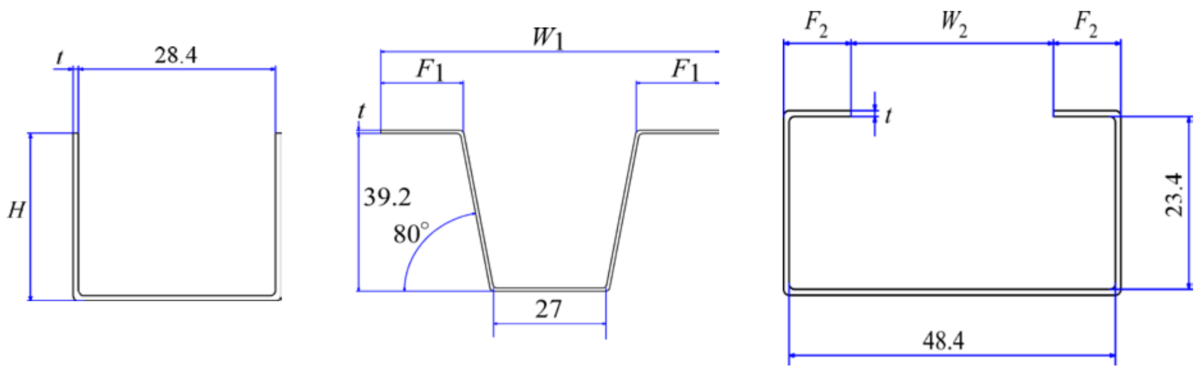
Chapter 1 Introduction

1.1 Background

The roll forming in Japan have been introduce since before the World War II. After the World War II, the demand for the steel product are increasing, and the use of roll forming machine become more important[1]. Roll forming also one of the primarily method to form metal in industry today[2,3]. Roll forming is a process of roll forming basically defined as a continuous, high-volume, fabricating process in which a desired cross-sectional profile is formed from a flat strip or sheet of metal by passing it through a series of tandem rolls[4]. Only bending process take place and the it is usually done at room temperature[5]. Roll forming compared to others manufacturing processes are high productivity beside able to form long length of metal sheet that hardly done by other manufacturing machine.

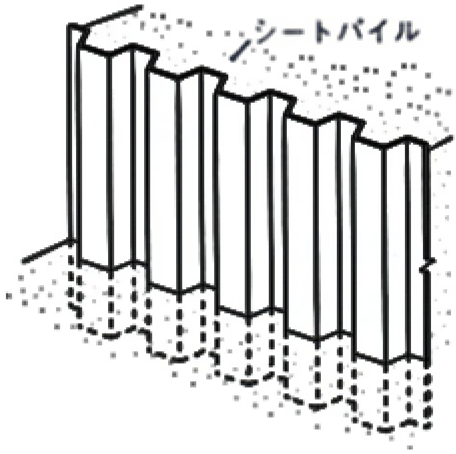
Among those product that have been produced by roll forming is light gauge channel steel. Light gauge channel steel is fabricated from a steel sheet. At presents, a lot of applications can be easily found in our surroundings. Light gauge channel steel is widely used in industries such as architecture[3], household products industry[4,5] etc. Figure. 1-1 shows the light gauge channel steel type, (a) light gauge channel, (b) hat channel and (c) c channel. One of the example of application of channel steel is the steel deck sheets used for roofs and floors provide support for gravity loads between the joists and/or beams[6]. Figure 2-1 shows image of (a) sheet pile and (b) deck plate[11,12]. For light gauge channel, the shape of cross-section parts, dimensions, tolerances and thickness has been specified. For example, SSC 400 material, yield points 245N/mm^2 and tensile strength 400～500N/mm^2 is already specified. [7]

Common problems in the handling of steel channel is when it's cut, to get the desired length, cut steel base channel is changed. When hat shape channel steel cut into specified length, the cutting edge of the product will change by the release of residual stress. This change is generally called cut end deformation. If deformation at cutting edge of the product in width is large, it will create some problems such in joining parts together like assembling components, butting the channel side-by side like building panels and can create product application and appearance problem. Moreover, when carrying out flying cut, if the edge of product changes immediately after cutting, it will lead to cogs breakage. Therefore, the process of amending the size of the edge which cut end deformation occurs at front end and tail end is needed. This will lead to poor production efficiency. Hence, development of the roll forming method without cut end deformation is desired.

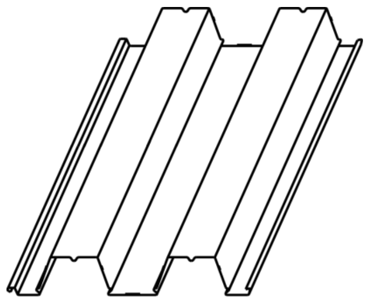


(a) Light Gauge Channel (b) Hat Channel (c) C Channel

Fig. 1-1 Cross section of light gauge



(a) Sheet pile



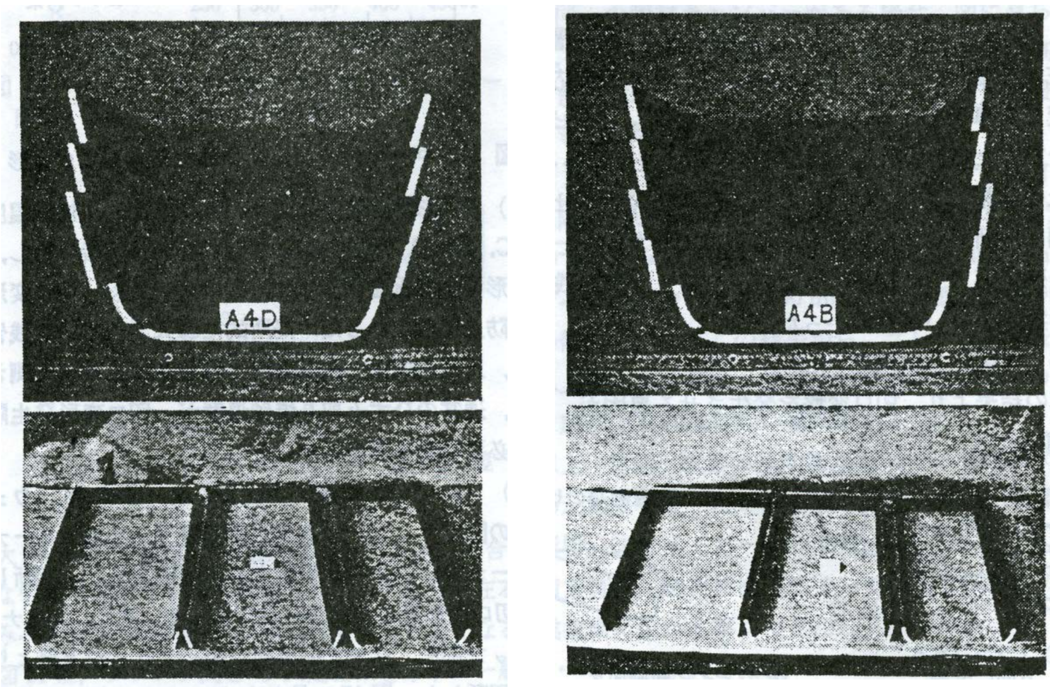
(b) Deck plate

Fig. 1-2 Example of channel steel application [11,12]

1.2 Previous Works

For channel steel, many papers have been published with respect to cut end deformation of channel steel. Kato et al.[13] 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.[14] 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.[15] described that the bending moment and torsional moment which act by contact with rolls were the main factor of cut end deformation. Some studies have been conducted in this way, but the relationships between bending deformation and residual stress in roll-formed channel remain uncertain.



(a) (b)

Fig. 1-3 Result of experiment done by Mihara et al. (a) The opening at front end (b) The closing at tail end. [14]

Additionally, sufficient information related to the mechanism by which released residual stress causes the cut end deformation remains unclear.

To date, beside of channel steel, research on cut end deformation of square channel steel by roll forming has been reported by Nagamachi et al[16,28]. X.P Wang et al [29] made research on cross section distortion due to cutting of cold-formed steel lipped C-section. In the research, The initial geometric imperfection of a cut stub column attains maximum values at the flanges, and is insignificant at the corners where the web and the flanges intersect. Holmas et al [17] mention about cut end deformation which is cause by internal stress which are balanced while the section is continuous, but become unbalanced as soon as the section is cut. Because of the author neither has sufficient data to specify these internal stress, the influencing factors of cut end deformation are frequently be identified.

Until now, the research on cut end deformation of hat shape channel steel by roll forming had been done by Nagamachi et al[18,19]. Also, Ona et al [30] done research on the eliminate distortion near cut of flange edge of channel section. This research will focus on the relation between cut end deformation of hat channel steel and residual stress together with mechanism of cut end deformation.

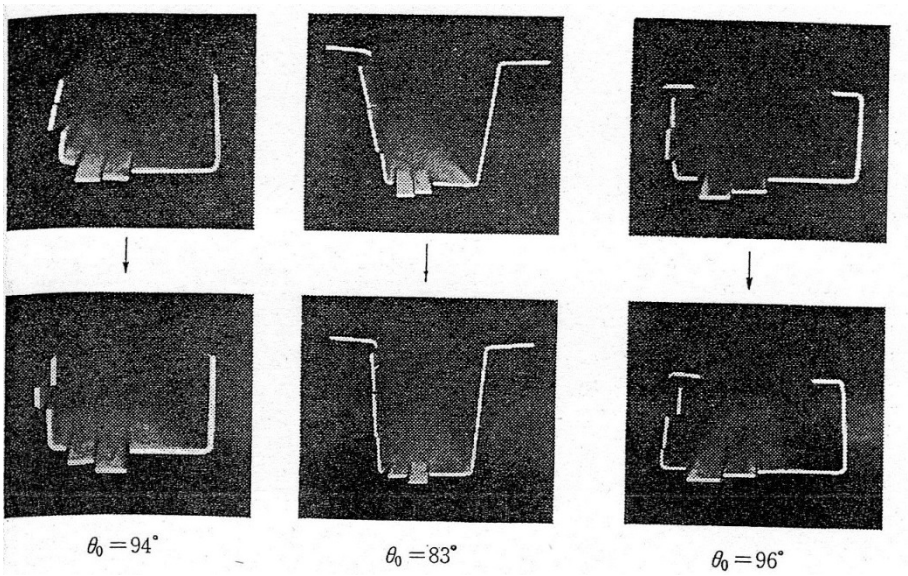


Fig. 1-3 Result of experiment done by Ona et al. Dimensional diagram in longitudinal direction after cutting. The upper diagrams show forming without overbend rolls and the lower diagrams show forming with overbend rolls. [30]

1.3 Contribution

It should be noted from the above literature review, however that limited studies are available on the details of the mechanism of cut end deformation and suggestion of eliminate cut end deformation by roll forming are hardly found. This has motivated the present study. This research 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 the 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. At the end of the research, method to eliminate cut end deformation of light gauge channel steel is proposed.

The contribution of this thesis can be discussed in details as follows.

- The mechanism of occuring of cut end deformation by residual stress and residual twisting moment was well explained. The influence factors of occuring cut end deformation could be reduse depend on choises and upon request for the metal processing company.
- The deformation at the end of cut end could eliminate by inserting inner rolls at the end of the finale tandem.

1.4 Thesis Organisation

After describing this introduction in **Chapter 1**, this thesis is organized as follows:

Chapter 2 intoroduces the cut end deformation of channel steel by roll forming.

Chapter 3 describe the cut end deformation of hat channel steel by roll forming.

Chapter 4 explain the method to eliminate cut end deformation of channel steel by roll forming by inserting inner roll.

Chapter 5 summarizes the result and discussion proposed in the thesis.

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Chapter 2 Cut End Deformation of Light Gauge Channel Steel by Roll Forming

2.1. 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. Commanly, when we talk about metal deformation, there are two type of deformation, which are plastic deformation and elastic deformation. The theory of plasticity describes the mechanics of deformation in plastically deforming solids, and, as applied to metals and alloys, it is based on experimental studies of the relations between stresses and strains under simple loading conditions. The main deformation occured in this research is plastic deformation. The basic quantities that may be used to describe the mechanics of deformation when a body deforms from one configuration to another under an external load are the stress, strain and strain-rate. [30]

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.

2.2 Methodology

Figure. 2-1 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. Rolls and their dimensions are presented in Fig. 2-2 and Table. 2-1. Table. 2-2 presents mechanical properties of sheet metal derived from tensile tests. These mechanical properties that are derived from tensile test represent the most important basis for a comparative evaluation of cold formability. That is why steel sheet producers and processors use the parameters of yeild stress, tensile strength, and elongation after the fracture for quality control. Besides, mechanical property values obtained by tensile test, two further characteristic are important within the scope of steel sheet developement. The normal anisotropy (r-value) and the strain-hardening exponent-1(n-values), [8,9] In this experiments, cold rolled forming is used and like any other method of steel sheet, many of the rolled sheets are classified as flat rolled product. [10]

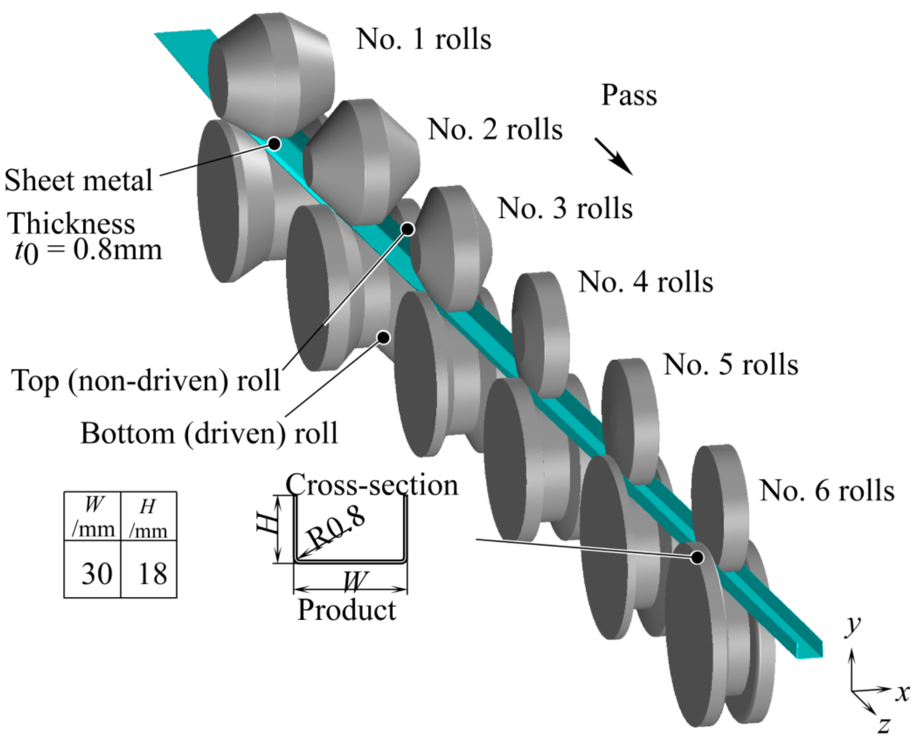

Fig. 2-1 Schematic illustration of forming process

Table. 2-1 Dimensions of forming rolls

Roll	D / mm	θ / °	L / mm
No. 1	135.5	30	28.90
No. 2	136.0	45	29.06
No. 3	136.5	60	29.26
No. 4	137.0	75	29.46
No. 5	137.5	85	29.84
No. 6	138.0	90	30.30

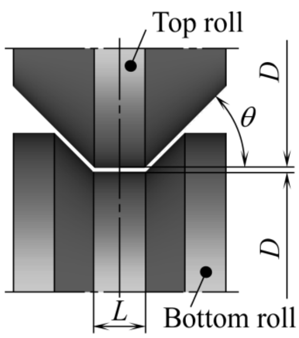

Fig. 2-2 Notations of forming rolls

The simulation process, depicted in Fig. 2-3, is explained as follows. First, simulation of the channel steel forming process is performed. In an experiment, a bottom roll is driven and a top roll is non-driven. The metal sheet velocity is V_z = 24 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.

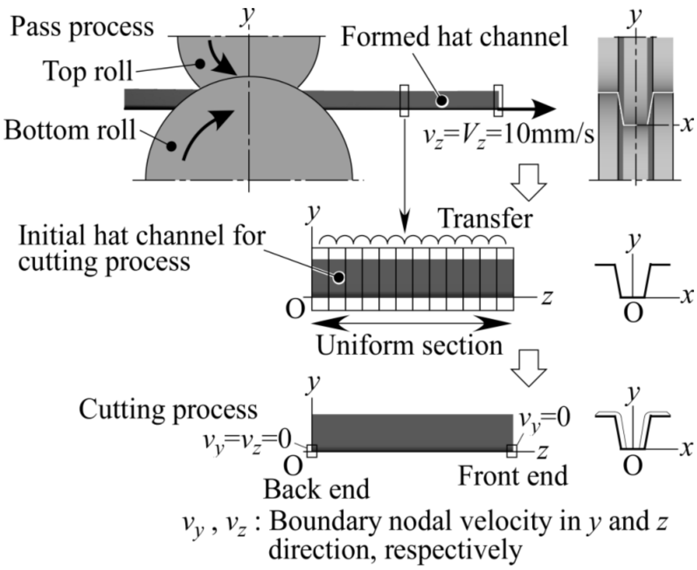

Fig. 2-3 Procedure of calculation for cutting process

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. This analysis conducted 3 elements thick direction. It is the minimum number of element divisions that can reproduce the analysis of elastic recovery, as understood by examination of the previous report[18,19]. 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.

2.3 Results and Discussion

2.3.1. Relation between the forming condition and cut end deformation

Notation representing the cut channel steel shape is portrayed in Fig. 2-4. For pass direction, we designated the z direction and the cutting edge as z = 0 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.

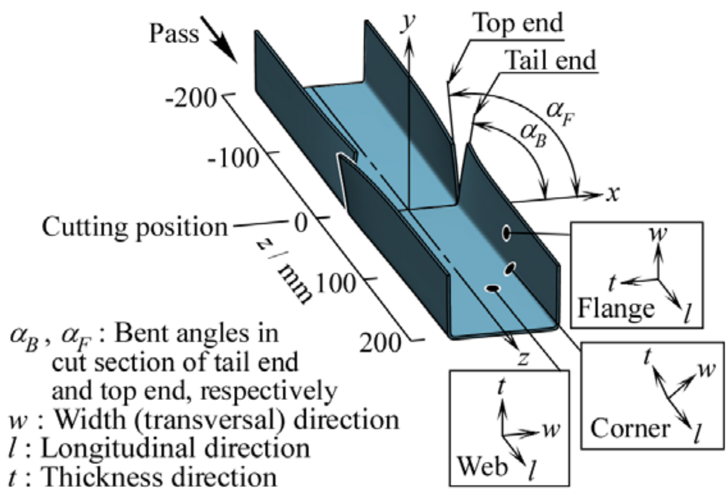

Fig. 2-4 Notations of representing shape of cut channel steel

Figure 2-5. shows the longitudinal distribution of the bent angle of cut channel steel. The bent angle in the cross section at z = 200 mm is in a stationary region defined as α_0. In addition, the bent angle at position of arbitrary z is defined as α. The absolute value of increment of bent angle $|\alpha-\alpha_0|$ is presented in Fig. 2-5. 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 α_F and α_B are defined respectively as the bent angle of the top end and the tail end. As depicted in Fig. 2-5, $\alpha_F - \alpha_0$ 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[15] 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. 2-6. The values $\alpha_F - \alpha_B$ of processes No. 1 and No. 2 are considerably large.

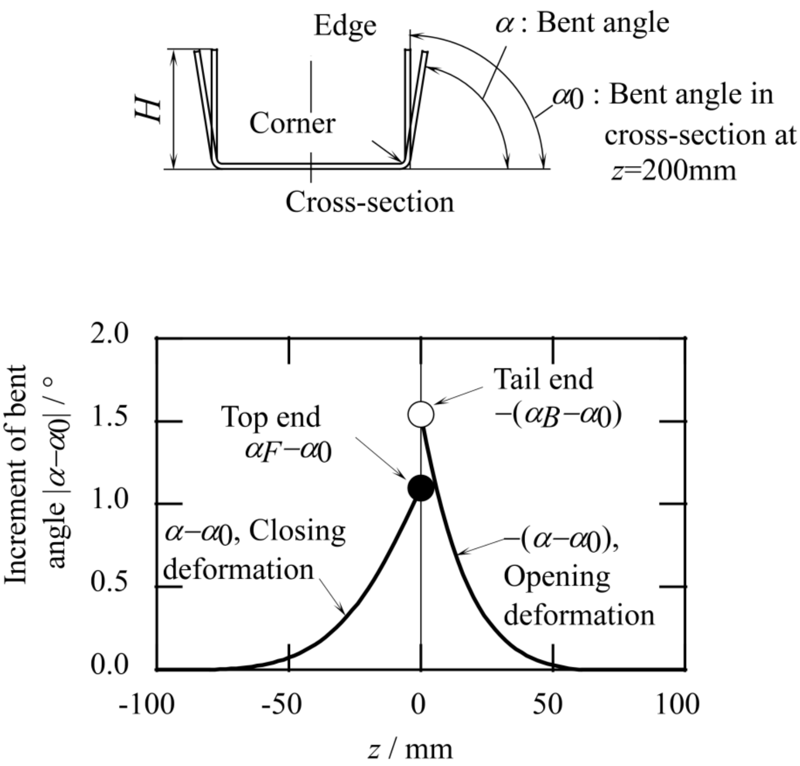

Fig. 2-5 Longitudinal distribution of increment of bent angle $\alpha - \alpha_0$ of cut channel steel

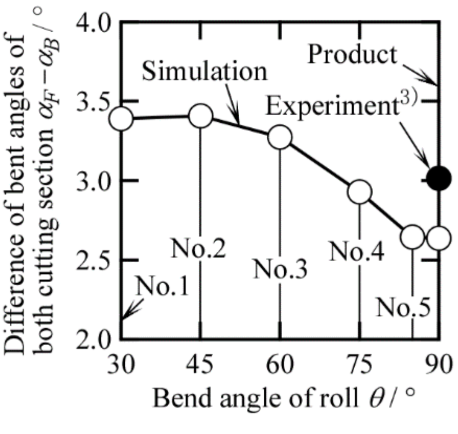

Fig. 2-6 Relationship of difference of bent angle of cutting section $\alpha_F - \alpha_B$ and bend angel of roll θ

2.3.2. 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 in transversal–longitudinal direction and in-thickness shear thickness-longitudinal direction[20]. 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 2-6 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 σ_w, longitudinal stress σ_l, shear stress in longitudinal-thickness (in-thickness) direction τ_{lt} and shear stress in transversal-longitudinal (in-plane) direction τ_{wl} are depicted in Fig. 2-7. 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 τ_{lt} shown in Fig. 2-7 is almost 0. We again performed a simulation with six layers in the thickness direction. The τ_{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.

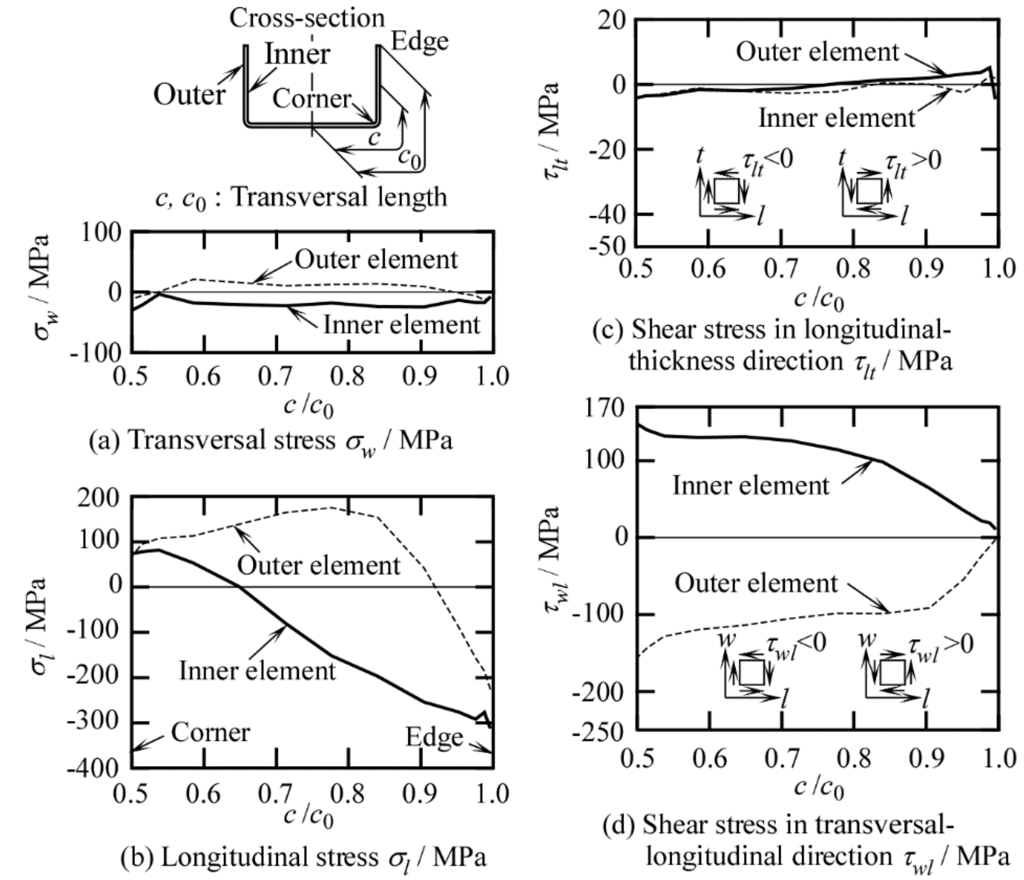

Fig. 2-7 Transversal distribution of residual stress in flange formed by No.1 rolls, simulation result

As portrayed in Fig. 2-7(b), in the wide domain of flange, the σ_l at the outer layer is tensile stress, whereas that at the inner layer is compressive stress. They are residual stresses. Similarly, Fig. 2-7(d) shows that the τ_{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 σ_l and τ_{wl} residual stresses. The generation mechanism is discussed in section 3.3. The value of transversal stress σ_w in Fig. 2-7(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[19]. Residual stresses σ_l and τ_{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.

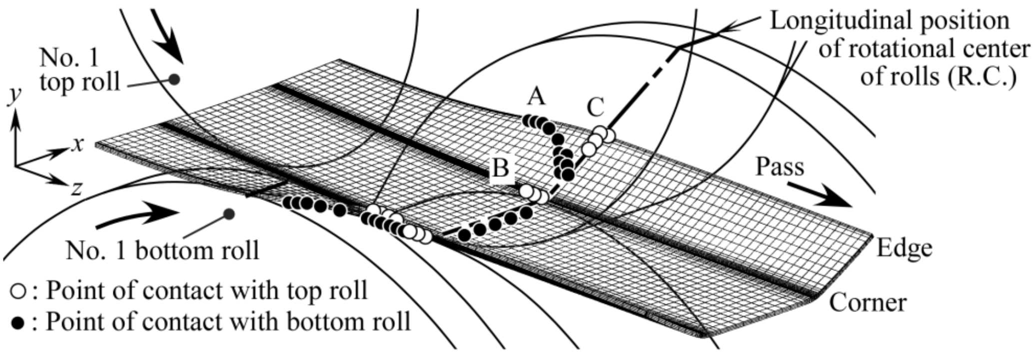

Fig. 2-8 3-dimensional shape and contact areas of channel steel being formed by No.1 rolls, simulation results

Figure 2-8. demonstrates the deformation state of channel steel being formed by No. 1 rolls and contact area with rolls. The dotted marks ○ and ● 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, 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. 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 time, 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.

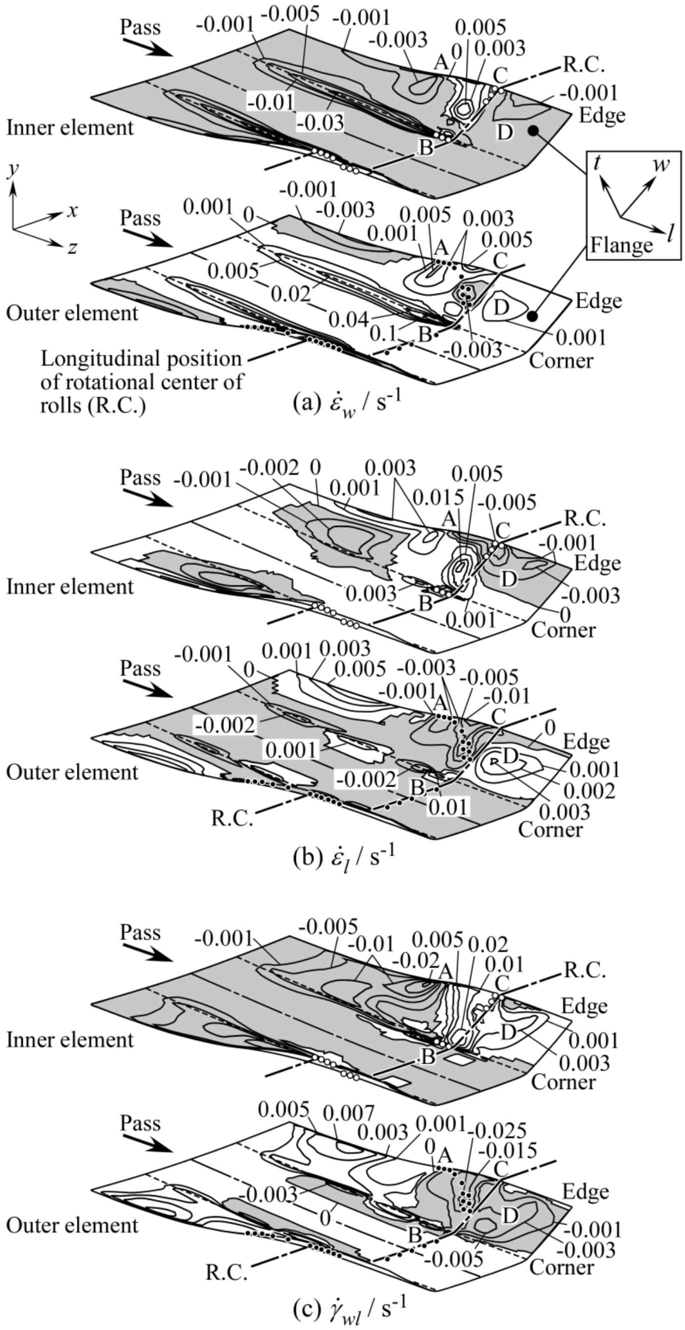

Fig. 2-9 Distribution of strain rate ($\dot{\varepsilon}^{p}_{w}$: transversal strain rate, $\dot{\varepsilon}^{p}_{l}$: longitudinal strain rate, $\dot{\gamma}^{p}_{wl}$: shear strain rate in transversal-longitudinal direction, they are plastic strain, respectively) in outer and inner elements of channel steel being formed by No. 1 rolls, simulation results, t0=0.8mm, H=18mm

Figure 2-9. demonstrates the distribution of plastic strain rate for inner and outer elements of channel steel being formed by No. 1 rolls. Figure 2-9(a), 2-9(b), and 2-9(c) respectively show the transversal strain rate $\dot{\varepsilon}^{p}_{w}$, longitudinal strain rate $\dot{\varepsilon}^{p}_{l}$ and shear strain in the transversal longitudinal direction $\dot{\gamma}^{p}_{wl}$. 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 $\dot{\varepsilon}^{p}_{w} > 0$, where deformation shows the bending concavely in the transversal direction. From position A to B, the inner layer is $\dot{\varepsilon}^{p}_{l} > 0$ and the outer layer is $\dot{\varepsilon}^{p}_{l} < 0$, where deformation shows the bending convexly in longitudinal direction because the flange follows the curve of the bottom roll, as already depicted in Fig. 2-8.

Next, we specifically examine the flange in the downstream domain from position R.C. In the figure, at around position D, both layer inner and outer are $|\dot{\varepsilon}^{p}_{w}| > 0$, $|\dot{\varepsilon}^{p}_{l}| > 0$ and $|\dot{\gamma}^{p}_{wl}| > 0$. In other words, plastic deformation occurs around position D. At this position, the inner layer is $\dot{\varepsilon}^{p}_{l} < 0$, the outer layer is $\dot{\varepsilon}^{p}_{l} > 0$, 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 $\dot{\varepsilon}^{p}_{l}$ and $\dot{\gamma}^{p}_{wl}$ of layers respectively coincide with the sign for σ_l and τ_{wl} shown in Fig. 2-9(b) and 2-9(d). 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 $\dot{\varepsilon}_w^p$ and $\dot{\varepsilon}_l^p$ presented in Fig. 2-9, in addition to the maximum principle strain rate and minimum principle stress rate calculated from simulations. Those illustrations are depicted in Fig. 2-10. The flange surrounded by A–B–C is bent along the curved surface of the bottom roll as depicted in Fig. 2-8 and Fig. 2-9. 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.

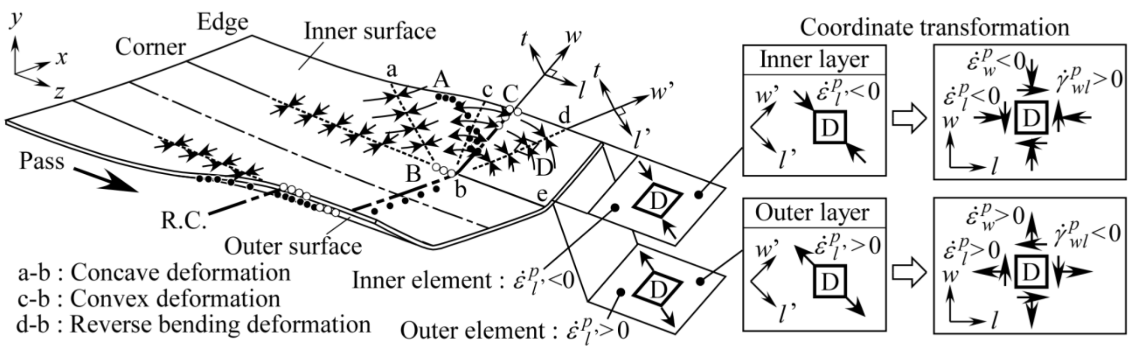

Fig. 2-10 Illustration of deformation of channel steel being formed by No.1 rolls and plastic strain

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 *t* direction. Those are depicted in Fig. 2-10. Reverse bending with the bending line in *w*' direction occurs. Consequently, the strain rate in the *l*' direction $\dot{\varepsilon}^p_l$ is compression ($\dot{\varepsilon}^p_l <$ 0) in the inner layer and tension ($\dot{\varepsilon}^p_l > 0$) in the outer layer. We consider a coordinate system based on the longitudinal direction (*l* direction). We transform $\dot{\varepsilon}^p_l$ into components in the *w*–*l*–*t* coordinate system. Those are $\dot{\varepsilon}^p_w$, $\dot{\varepsilon}^p_l$ and $\dot{\gamma}^p_{wl}$ as present in right panel of Fig. 2-10. If it does so, then $\dot{\varepsilon}^p_l$ is compression ($\dot{\varepsilon}^p_l < 0$) in the inner layer, $\dot{\varepsilon}^p_l$ is tension ($\dot{\varepsilon}^p_l > 0$) in the outer layer, $\dot{\gamma}^p_{wl}$ is plus ($\dot{\gamma}^p_{wl} > 0$) in the inner layer and $\dot{\gamma}^p_{wl}$ is minus ($\dot{\gamma}^p_{wl} < 0$) in the outer layer. As depicted in Fig. 2-9(b) and Fig. 2-9(c), $\dot{\varepsilon}^p_l > 0$ and $\dot{\gamma}^p_{wl} < 0$ in the inner layer near D, whereas $\dot{\varepsilon}^p_l > 0$ and $\dot{\gamma}^p_{wl} < 0$ in the outer layer near D. Each sign (positive or negative) corresponds with the sign in the right panel of Fig. 2-10. Furthermore, as portrayed in Figs. 2-7(b) and 2-7(d), each sign of σ_l and τ_{wl} which are residual stresses corresponding with the sign of $\dot{\varepsilon}^p_l$ and $\dot{\gamma}^p_{wl}$ near D in Figs. 2-9(b) and 2-9(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.

2.3.3 Generation mechanism of cut end deformation

As depicted in Fig. 2-10, 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.

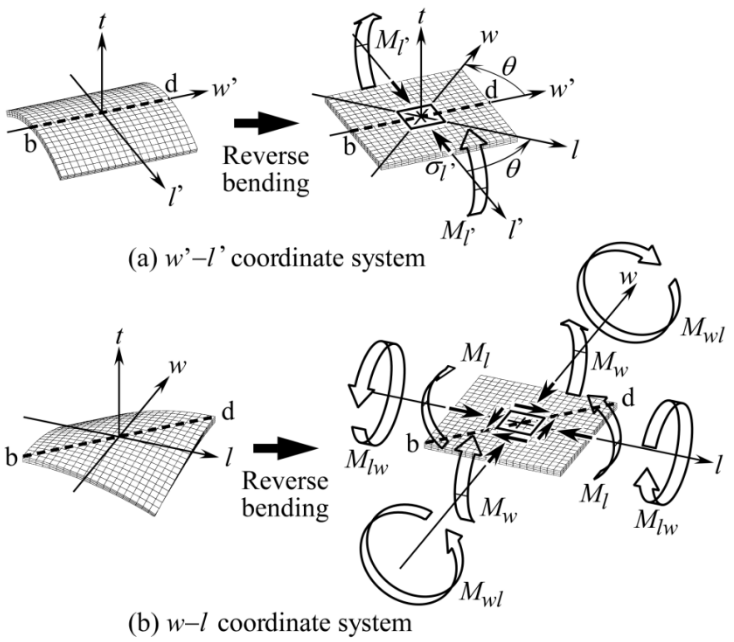

Fig. 2-11 Schematic illustration of bending and twisting moments

Figure 2-11 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.

$$M_{l'} = \int \sigma_{l'}\ t\ dt \qquad (1)$$

Therefore, it is the same as $M_{l'}$ remains that $\sigma_{l'}$ remains. 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 θ, the bending moment and twisting moment are shown as presented below[21]

$$\left.\begin{aligned} M_w &= M_{w'}\cos^2\theta + M_{l'}\sin^2\theta - M_{w'l'}\sin2\theta \\ M_l &= M_{w'}\sin^2\theta + M_{l'}\cos^2\theta + M_{w'l'}\sin2\theta \\ M_{wl} &= \frac{M_{w'} - M_{l'}}{2}\sin2\theta + M_{w'l'}\cos2\theta \\ M_{lw} &= -M_{wl} \end{aligned}\right\} \qquad (2)$$

Here, the $M_{w'}$, M_w, 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. 2-11 (a), by assuming

$$\left.\begin{aligned} M_w &= M_{l'}\sin^2\theta \\ M_l &= M_{l'}\cos^2\theta \\ M_{wl} &= \frac{M_{l'}}{2}\sin2\theta \\ M_{lw} &= -M_{wl} \end{aligned}\right\} \qquad (3)$$

only M_l acts, $M_{w'} = 0$ and $M_{w'l'} = 0$, the (2) equations are shown as presented below.

$$\left.\begin{aligned} M_w &= \int \sigma_w \, t \, dt \\ M_l &= \int \sigma_l \, t \, dt \\ M_{wl} &= \int \tau_{wl} \, t \, dt \end{aligned}\right\} \qquad (4)$$

Figure 2-11(b) presents these moments schematically. In addition, the M_w, M_l and M_{wl} per unit width is presented below[21]. 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. 2-12. We examine each of the releases of the bending moment and torsional moment. They are depicted respectively in Fig. 2-12(a) and 2-12(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 M_w is attributable to deformation in springback.

In Fig. 2-12(a), both the top end and tail end have opening deformation by release of bending moment M_l . In Fig. 2-12(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. 2-5. Ona et al.[15] described that the factor of cut end deformation is the bending moment and twisting moment that arise by contact with a roll.

This research 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.

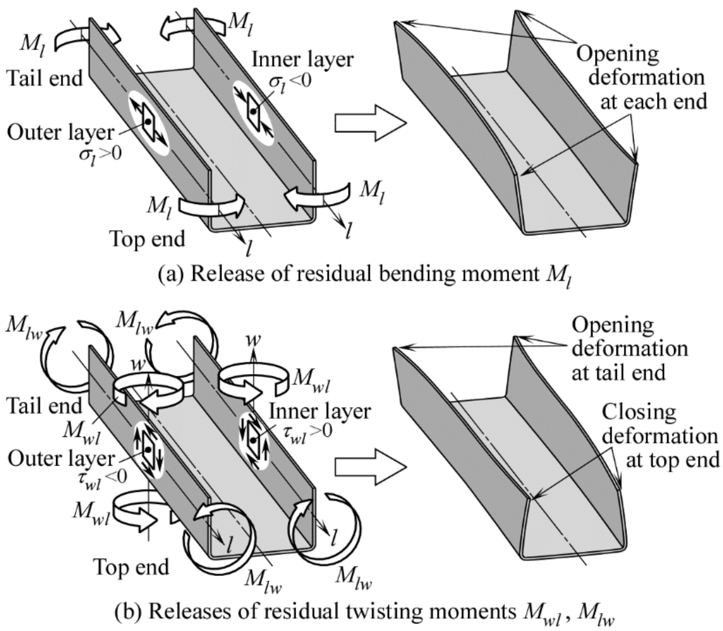

Fig. 2-12 Mechanism of end deformation by releases of residual bending moment and residual twisting moments

2.4. 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 formed by rolls is bent. In fact, it is bent reversely with 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) Both the top end and tail end of the cutting edge have opening deformation by release of the residual bending moment. The top end has closing deformation. The tail end has opening deformation by release of residual twisting moments. The opening deformation at the tail end is large because of the overlap of the two deformations.

Chapter 3 Cut End Deformation of Hat Shape Channel Steel by Roll Forming

3.1 Introduction

A hat channel, also called a furring channel, is a channel with a bottom horizontal web and two vertical flanges, as well as an outward lip that is fabricated via roll forming. When the channel is cut off at a specified length, the edge of the product will change via the release of residual stress, and this change is generally called cut end deformation. The cut end deformation of channel steel was investigated via experiment and three-dimensional finite-element simulation. The effect of initial thickness on the cut end deformation of hat channel steel was studied. The experimental [3] result and FEM result showed that the thinner the initial thickness, the smaller the residual stress value. Also, the influence of lip length on the cut end deformation of hat-shape channel steel is small.

3.2 Methodology

Figure 3-1 present a schematic view of the forming process used for this research. In this research, cut end deformation of hat shape channel steel and its mechanism was investigated by experiment and three-dimensional finite element simulation. First, 6 tandem of rolls, No1~No 6 are built and 4 size of flange, 0mm, 9mm,16mm and 23mm channel steel are formed by this rolls. The schematic diagram of a forming process, and the sign and size of forming rolls are shown in Fig. 3-1 and Fig. 3-2, respectively. The interval between roll and roll is 375 mm. Then, from experimental results, relation between simulation result and experimental result is compared.

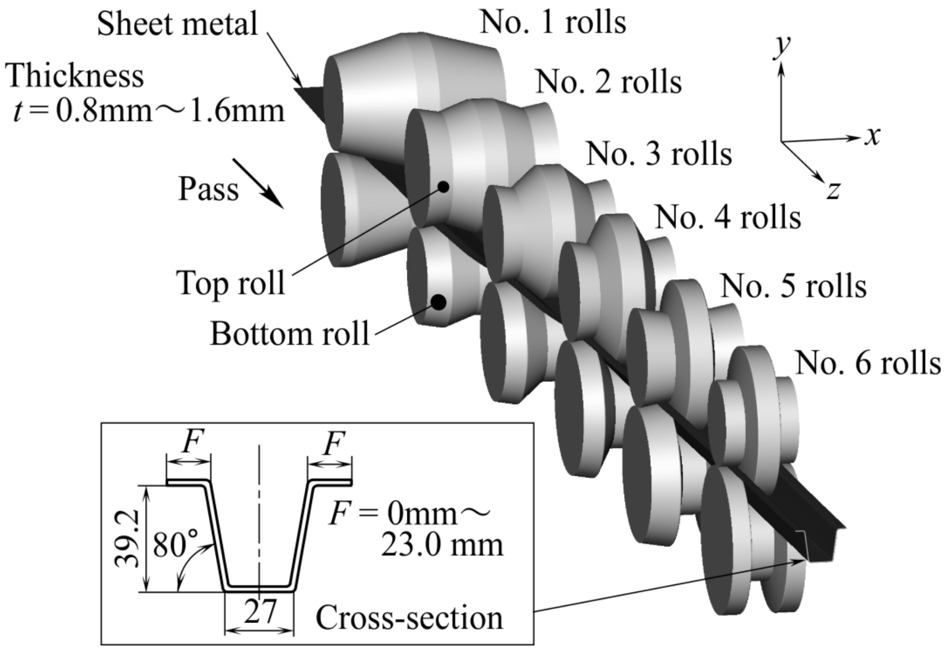

Fig. 3-1 Schematic diagram of forming process

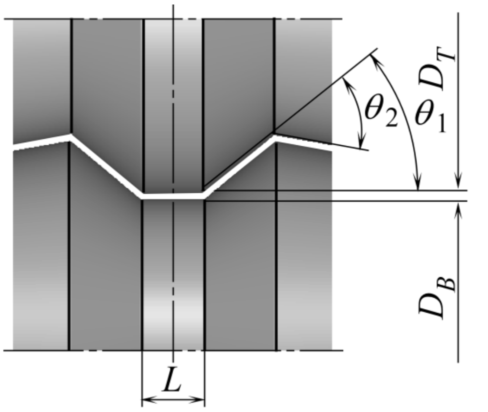

Fig. 3-2 Notations of forming roll

Table 3-2 Dimensions of forming roll

Roll	D_T /mm	D_B /mm	θ_1 / °	θ_2 / °	L /mm
No. 1	160.0	100.0	15	0	27.88
No. 2	160.5	100.5	20	30	27.96
No. 3	161.0	101.0	40	50	28.32
No. 4	181.5	101.5	60	70	28.84
No. 5	182.0	102.0	75	85	29.44
No. 6	182.5	102.5	80	80	29.68

The simulation is conducted using by transient elastic-plastic analysis by a static implicit method. Element used for simulation are 8 node hexahedron (bricks), and the software used is analysis code DEFORM-3D Ver. 10.1. In the code, Young's modulus was 206.8 GPa, Poisson's ration 0.3, Yield stress was 250.8 MPa, n value was 0.250 and tensile strength was 388.8 MPa. Blank sheet with 760 mm length was used in the simulation. First, forming simulations for each of roll sets Nos. 1, 2, and 3 were conducted separately using the procedure described in reference 7. Then, cutting process were simulated using the process which are describe in8) as follows. (1) Select one 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 pipe end deformation by displacement of nodes that produce a force imbalance. Numerous elements in the thickness direction are necessary to calculate the deformation of elastic recovery.

3.3 Result and Discussion

3.3.1 The effect of lip on cut end deformation of hat channel steel

The definition of a sign which express cut end deformation is present in Fig. 3-3. In the Fig. 3-3, x_0 is standard width, x_F is top end width, x_B is tail end width. Fig. 3-3 also demonstrate the direction for each plane where longitudinal direction shown by l direction, thickness shown by t direction and width (transversal) direction shown by w direction. Next, the relation between cut end deformation and lip's length is express in the Fig. 3-4. Also, the open symbol (○, △) stands for the width of the cutting section of the front end, and the solid symbol (●, ▲) stands for the width of the cutting section of the back end. From the figure, we can say that the simulation results agree with the experimental[15] results relatively well.

Figure 3-4 and Fig. 3-5 depicts the relationship between the width of the cutting section and lip length. The results obtained show that the deformation zone changes when the lip length changes and that the front end and back end show different amounts of deformation. When F=0mm, the front end value, *(xF -*

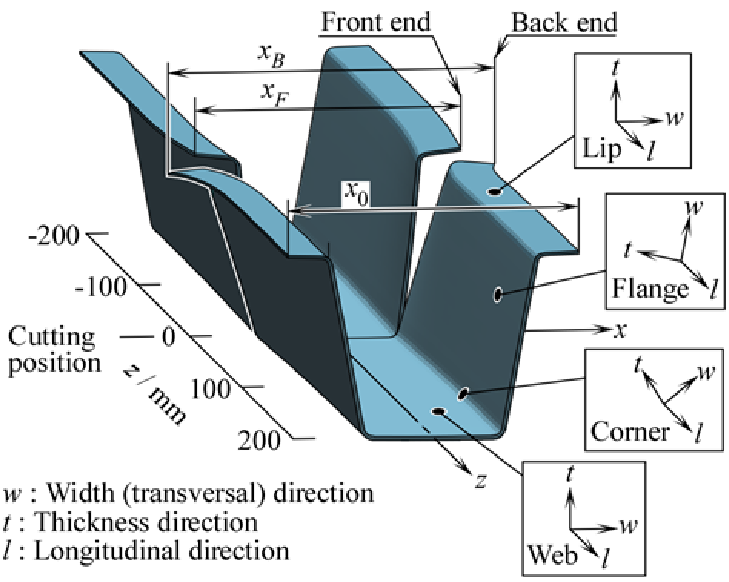

Fig. 3-3 Notation to representing shape of cut hat channel

x0) /2, is negative, and the tail end value, *(xB - x0) /2*, is positive, whereas when F=3mm, 9mm, 16mm or 23mm, both the *(xF - x0) /2* and *(xB - x0) /2* values are positive. The results indicate that steel channel without a lip (F=0mm) has a closing deformation at the front end and an opening deformation at the tail end, while channel steel with a lip (F=3mm, 9mm, 16mm or 23 mm) has an opening deformation at both front and tail end. The back end values are larger than the front end values, suggesting a larger opening deformation at the back end. A simulation was performed for 3mm of lip length (this was not performed experimentally) and t=0.8mm, as demonstrated in Fig. 4. Interestingly, a channel with even a small lip will result in an opening deformation at the back end.

It is believed that cut end deformation of product formed by roll forming is cause by shear stresses in thickness-longitudinal direction and longitudinal-peripheral direction. Yet very few studies have examined and explain in detail the generation mechanism of cut end deformation and the causes. Next session, 3.3.2 therefore, set out to discuss in details on residual stress that causes cut end deformation of hat steel channel.

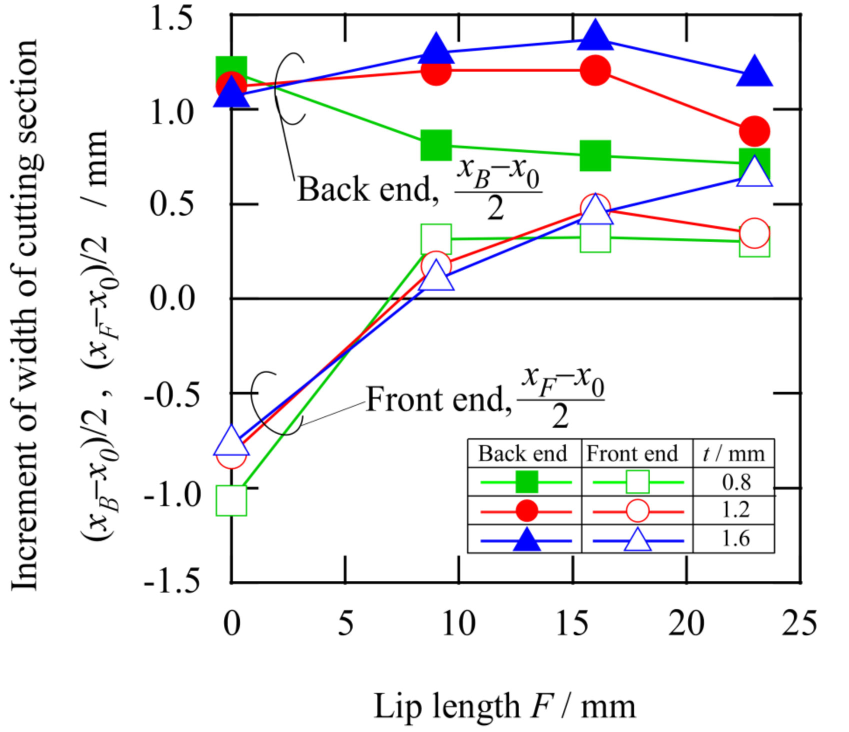

Fig. 3-4 (a) Relation between increment of width of cutting section and lip length (Experimental)

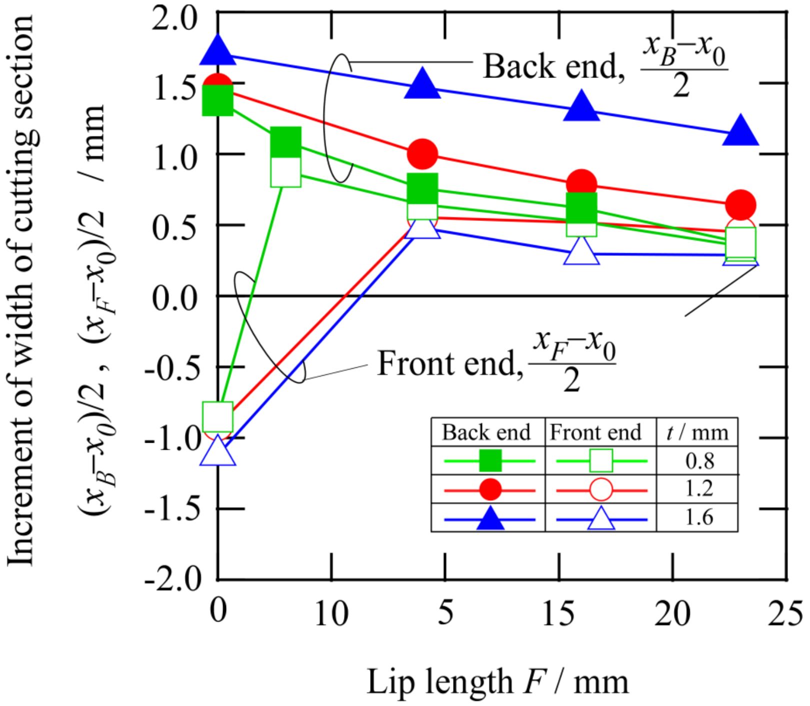

Fig. 3-4 (b) Relation between increment of width of cutting section and lip length (Simulation)

3.3.2 The effect of residual stress on cut end deformation

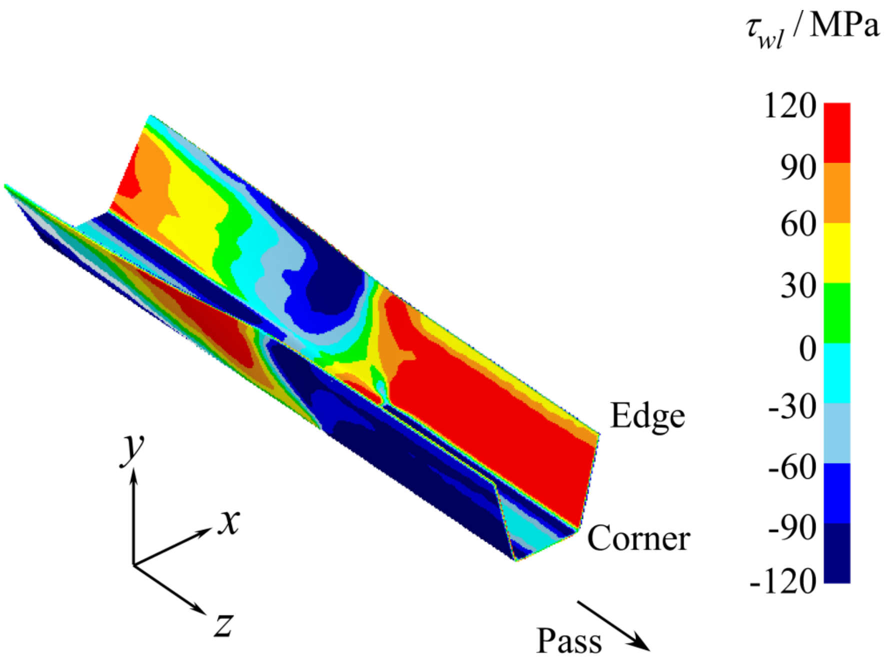

Fig. 3-5 (a) Distribution of residual stress τ_{wl} (shear stress in transversal-longitudinal) of hat channel being formed by No. 5 rolls, F = 0 mm (t =1.2 mm)

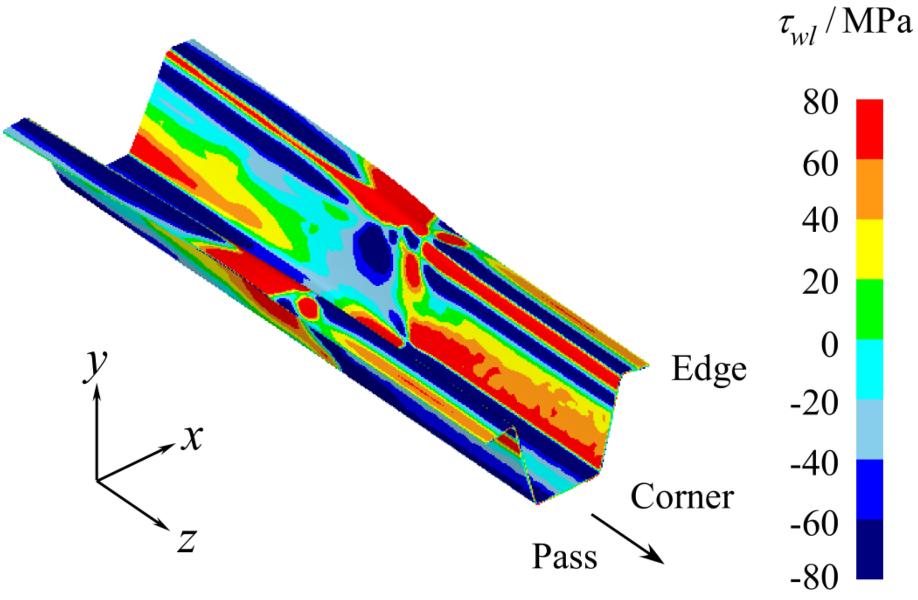

Fig. 3-5 (b) Distribution of residual stress τ_{wl} (shear stress in transversal-longitudinal) of hat channel being formed by No. 5 rolls, F = 9 mm (t = 1.2 mm)

We will discuss the residual stress by referring to Fig. 3-5(a) and 3-5(b) above. Fig. 3-5 depicts the distribution of residual stress twl (shear stress in the transversal-longitudinal direction) of the channel being formed. In Fig. 3-5, the colour red shows tensile stress, and colour blue shows compressive stress . First, we discuss the case of a channel without a lip, F=0mm. As shown in Fig. 3-5(a), regarding the shear stress for a channel without a lip in the transversal-longitudinal twl direction, the occurrence of a large tensile residual stress at the inner plane and a large compressive residual stress at the outer plane can be seen.

When F=0mm, the inner plane twl is positive, and the external plane twl is negative. The flange becomes bent, rebent, and reverse bent by the effect of roll forming in the longitudinal direction. Given the position of the centre of roll rotation, the lower part will receive the last reverse bend, which is the reason residual stress occurs. Based on the detailed simulation results, it is believed that the bend return is a twist return and that the twisting moment affects the flange of the product. If the residual twisting moment is released, the front end will be closed, and the back end will be open.

During the roll forming process, concave, convex and reverse bending deformations of the flange take effect and cause the bending lines to diverge from the contact point between the top roll and the corner of the flange. The reverse bending deformation is caused by the bending moment and the twisting moment. The residual twisting moment is also known as the residual in-plane shear tress. These moments remain on the flange. When channel steel is cut, the release of the bending moment results in the opening of both the front end and the tail end. At that moment, in the F=0mm case, the release of the twisting moment makes the flange close at the front end and open at the tail end.

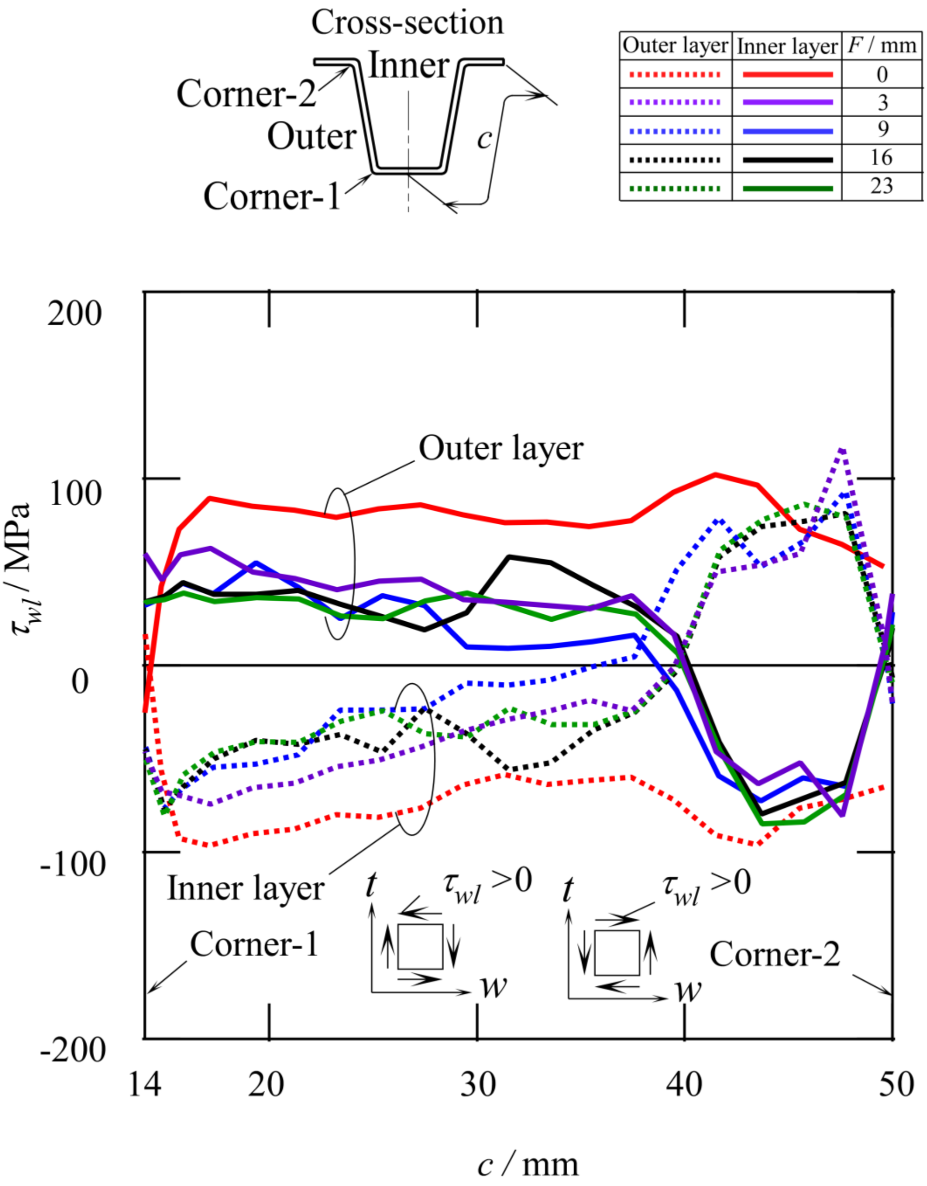

Fig. 3-6 (a) Transversal distribution of residual stress τ_{wl} (shear stress in transversal-longitudinal direction) in flange at z =200 mm, simulation results (t = 0.8 mm)

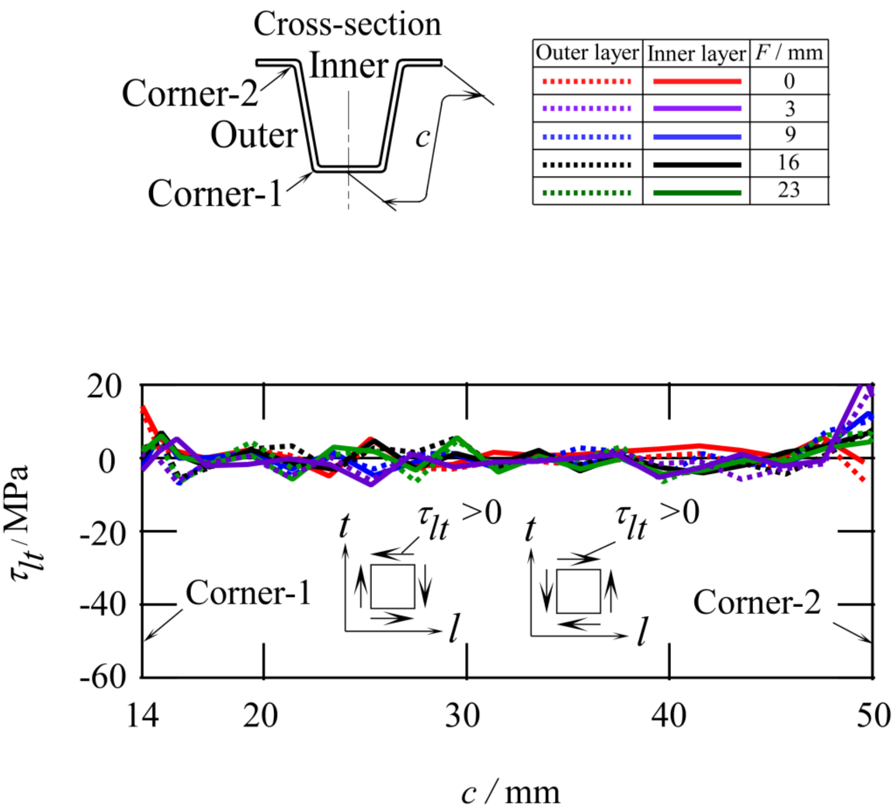

Fig. 3-6 (b) Transversal distribution of residual stress τ_{lt} (shear stress in longitudinal-thickness direction) in flange at z =200 mm, simulation results (t = 0.8 mm)

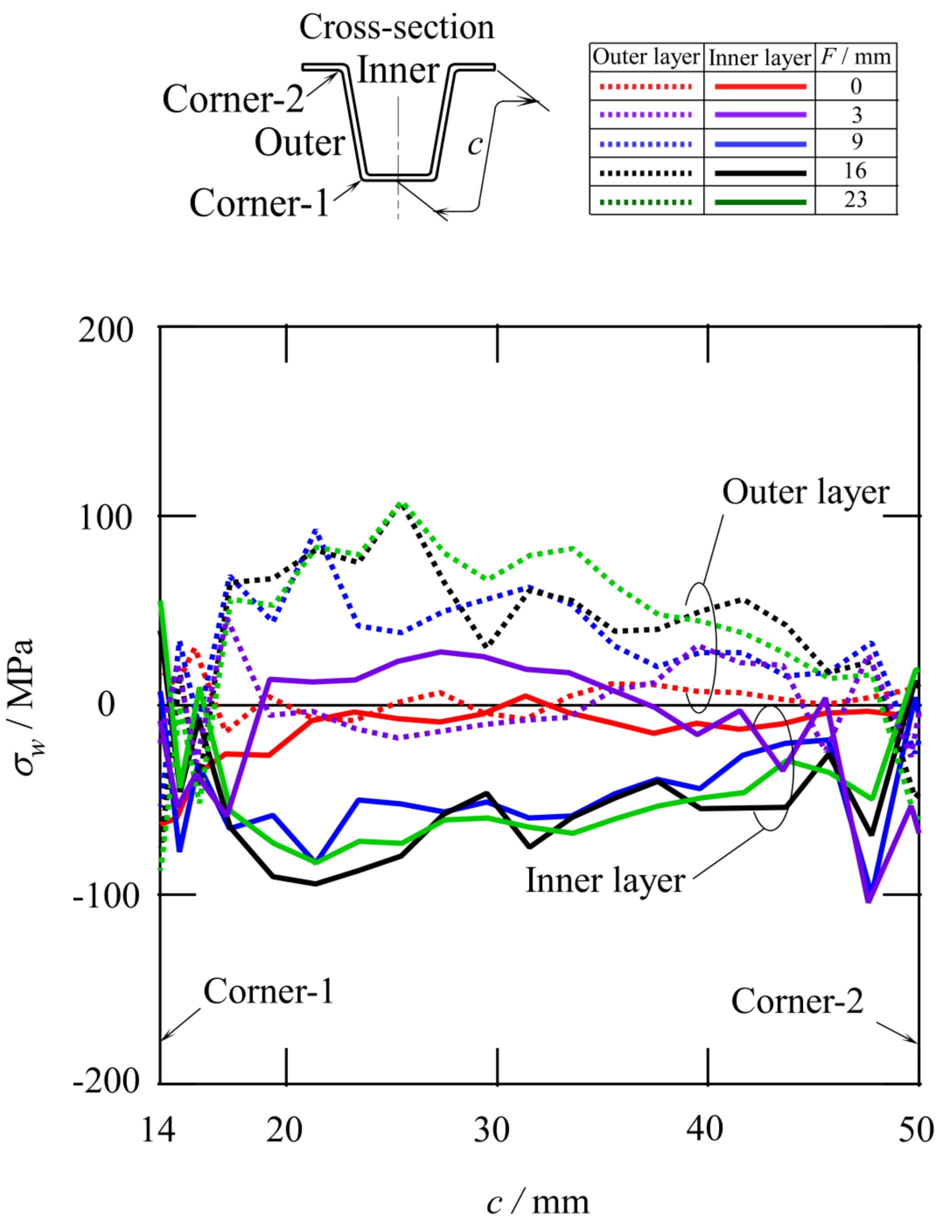

Fig. 3-6 (c) Transversal distribution of residual stress σ_w (transversal stress) in flange at *z* =200 mm, simulation results (t = 0.8 mm)

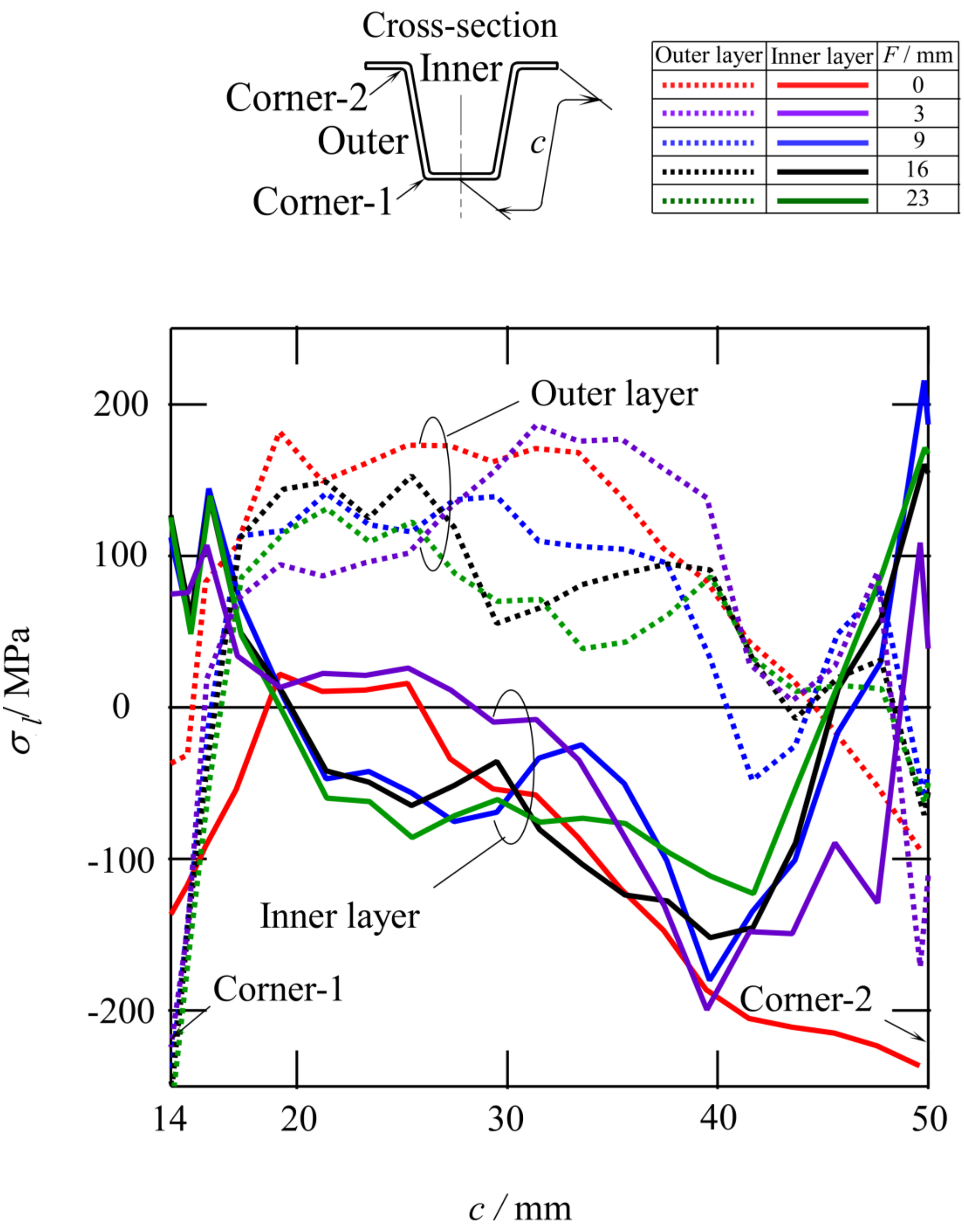

Fig. 3-6 (d) Transversal distribution of residual stress σ_l (longitudinal stress) in flange at z =200 mm, simulation results (t = 0.8 mm)

Fig. 3-6 shows that for a deformation that opens the front end and the back end, the in-plane value is negative for the inside and the external plane value is positive for the outside in the large domain of the flange. This residual stress in the longitudinal direction, along with the reverse bending in longitudinal direction, is the reason the bending moment remains in the flange of the product. If the residual bending moment is released, both the front end and the back end will open.

On the other hand, when F = 9 mm, 16 mm, or 23 mm, the in-plane twl will be positive when $14\ \mathrm{mm} < c < 40\ \mathrm{mm}$ and negative when $40\mathrm{mm} < c < 50\mathrm{mm}$. The sign of external plane twl will be the opposite of the in-plane value’s sign. The bottom part of the flange (c=14 mm∼40 mm) and the top part of the flange (c = 40 mm∼50 mm) have different residual twisting moments. If the moments are released, cut end deformations with reversed openings and closings will occur on the top and bottom parts. It is believed that the torsion moments, which are mutually offset, are the reason that the deformation that occurs is reduced.

3.3.3 The effect of inital thickness to cut end deformation of hat channel steel

In this part, the relationship between cut end deformation and steel sheet thickness were discussed. Fig.3-7 (a),(b) and (c) respectively show the relation between increments of width of cutting section, and lip length. Also, the camparison between 3 types of steel sheet thickness, 0.8mm, 1.2 mm and 1.6 mm. In Fig.3-7, red color represent experimental[15] result while blue color represent simulation result. Meanwhile, open symbol (o,△) stand for the lip length for the front end and solid symbol (●,▲) stand for the lip length for the back end. The horizontal axis show lip length which were 0mm, 9mm, 16mm and 23mm for 3 types of metal sheet thickness which were 0.8mm, 1.2mm and 1.6mm respectively. The simulation results agrees relatively well with the experimental results in Fig. 3-7 (a), 3-7(b) and 3-7(c).

Channel with 0mm lip had opening at the front end and closing at the back end while channel with lip are all positive, which indicate opening deformation. Back end values are larger than those front end values, suggesting larger opening deformation at the back end. Simulation was done on the 3mm of lip length as demonstrate in Fig 3-7 (a). What is interesting in this data is that channel with lip even small, results on opening deformation at the back end.

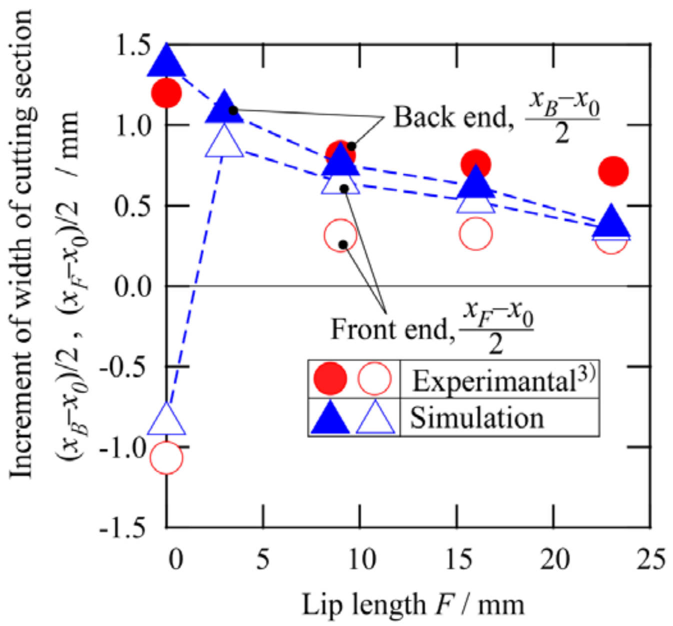

Fig. 3-7 (a) Relation between increment of width of cutting section and lip length (t = 0.8 mm)

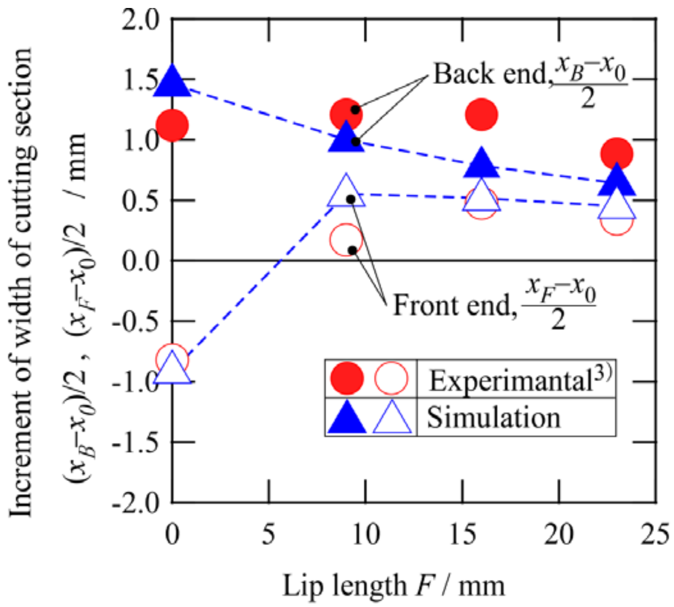

Fig. 3-7 (b) Relation between increment of width of cutting section and lip length (t = 1.2 mm)

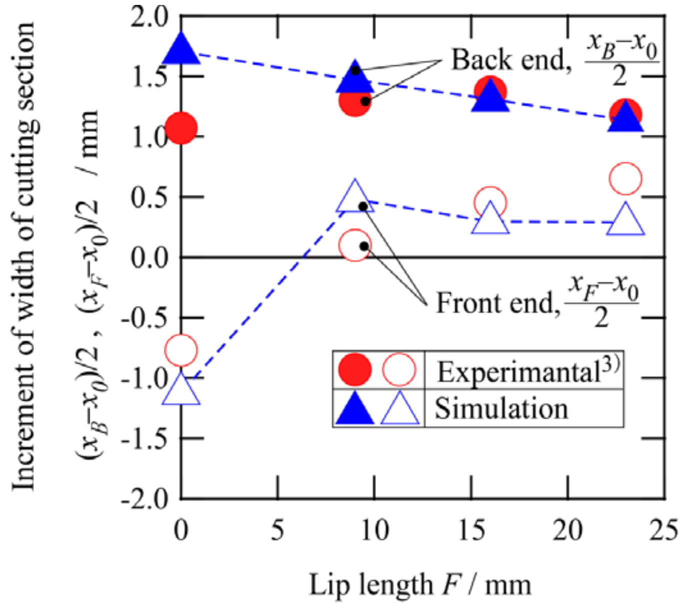

Fig. 3-7 (c) Relation between increment of width of cutting section and lip length

Fig. 3-8 (a) demonstrate the contact condition between hat channel and rolls when lip is 9mm. Black dot show the contact point with bottom roll and white dot show the contact point with top roll. The mechanism of the bending of steel sheet will be explained. First, steel sheet is moving from left to the right. Then, the flange touch with bottom roll along with bottom roll, flange is bended inside. The lip also touch with top roll, and lip is bended outside. The upper part of flange is stretch out inside. Top roll and flange touch each other, and then along the top roll, the flange is stretch out outside. As well as when flange bent outward, when flange release from the roll, the flange is force to return to initial shape, which force the flange to become straight, and this is explained in Fig 3-8 (b). The occurrence of bending, opposite bending and reverse bending of bending line by elongation of radial from the center of the rotation when flange being bent by roll. The bending moment and twisting moment result in reverse bending at downstream area rather than center of rotation area. The residual shear stress, residual moment describe on above are because of the reverse bending of stress in longitudinal direction and transverse-longitudinal direction. As presented in Fig 3-7(a) ,(b) and (c), it is known that the opening and closing of cut end deformation is not definitely affected by the initial thickness of the hat channel steel.

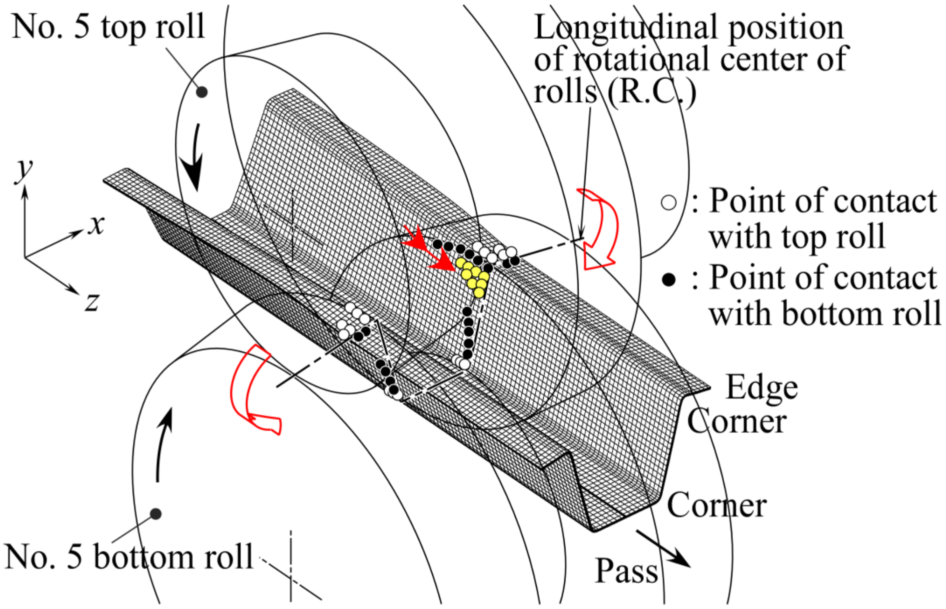

Fig. 3-8 (a) 3-dimensional shape and contact areas of hat channel being formed by No. 5 rolls, F=9 mm(t = 0.8 mm)

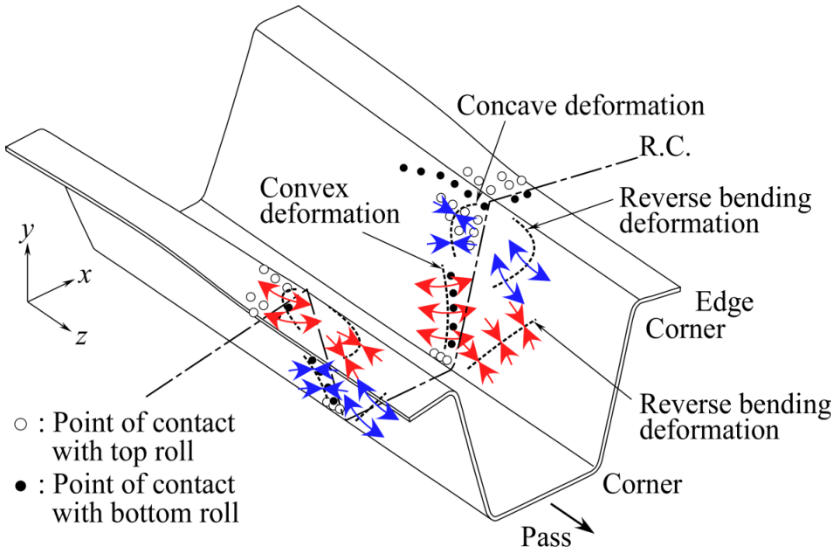

Fig. 3-8 (b) Illustration of deformation of hat channel being formed by No. 5 rolls, F=9 mm(t = 0.8 mm)

3.4 Conclusion

1) A hat steel channel without lip will flair in (closing) at the top end and flair out (opening) at the tail end when cut off into component, differ to hat steel channel with lip will flair out (opening) at the both top end and the tail end.

2) Large residual shear stress in the transversal-longitudinal direction τ_wl at the edge affecting the outer and the inner layer result in cut end deformation. For hat channel with lip, opposite direction of residual twisting moment occurs at the upper part and lower part of flange. Those stress and moments offset each other making the cut end deformation small at cutting edge.

Chapter 4 The Forming of Channel Steel Combine with Inner Roll

4.1 Introduction

In the previous chapter, by performing a finite element simulation of the cutting process and the roll-forming process of the channel steel, the residual shear stress in the inner layer are in different directions at the inner and outer layer is the factor of the occurrence of cut end deformation which result in opening at the back end and closing at the tail end. Few method has been reported in order to eliminate cut end deformation, which are over bending method by side rolls without using inner roll. The experiment has been done on overbend method and repeat bending method, but there was no effect at cut end deformation[23]. Until now, methods for eliminating cut end deformation has been proposed so far, using a small inner roll forming of U-shaped steel.[14,20] Therefore, this research will verify the methode to eliminate cut end deformation by applying a small inner roll at finale tandem of the roll forming process. In this research, finite element method (FEM) is used and the mechanism of the cut end deformation by inserting inner roll will be discussed.

In the previous report [26], by performing a finite element simulation of the cutting process and the roll-forming process of the channel steel, the residual shear stress in the inner layar are in different directions at the inner and outer layer is the factor of the occurrence of cut end deformation which result on opening at back end and closing at tail end. There is a few method have been reported in order to eliminate cut end deformation, which are over bend method[23] and side roll press method. Experiment have been done on overbend method and repeat bending method, but there was no effect at cut end deformation. Untill now, inner rolling method was proposed to encounter the cut end deformation. In the [17]this method shown a great result to eliminate cut end deformation for U rib forming etc. In 1980, Mr Mihara in his writing says that the inner and the outer rolls used in u-shaped rib give effect to the cut end deformation, and it is said that, the closing at front end and opening at tail end turns into opening at front end and closing at back end by enlarging the amount of the bending-back. Previously, In the Mr Kaji roll-forming public presentation seminar, Mr Kaji also shown that an inner side roll has an effect in cut end deformation, and drum type inner roll is more effective. For this reason, this method was applied on channel steel and simulation was done.

Then, as a finishing process after fabrication of a product, the No.7 outer roll and No.8 inner roll were attached. Therefore, this research will verify the methode to eliminate cut end deformation by applying a small inner roll at finale tandem of the roll forming process. In this research, finite element method (FEM) is used and the mechanism of the cut end deformation by inserting inner roll will be discussed.

4.2 Methodology

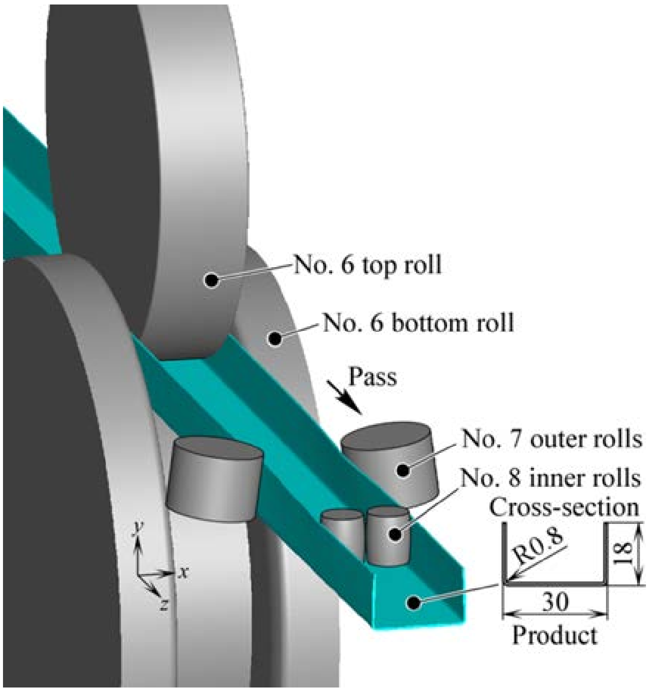

Fig. 4-1 Schematic diagram of forming process

A metal sheet is bent by the corner position of the roll forming from rolls No.1 ~ No.6. First, the metal sheet is bent. Then, a flange is formed in this process. Finally, the product, which has a hat channel, is fabricated. The forming process and roll dimension is similiar the previous paper[29]. In this research, the finishing process was performed by over bending at No.7 roll and reverse bending at No.8 roll. Fig. 4-1 and Fig. 4-2 shows the schematic diagram of finishing process and the arrangements and dimension of the No.7 and No.8 rolls respectively. Table 2-2 in the chapter 2 shows the mechanical properties of metal sheet. The simulation was conducted using a static implicit scheme applied to transient elasto-plastic analysis. The analysis domain for FE is cut by hexahedral elements with eigh nodes and a general code of DEFORM-3D Ver.6.0 was used for calculation. 750mm of the model element is used for analysys forming process in the longitudinal direction and total number of 35000 elements is set in 3 element in thickness direction. The analysis of a cutting process produces a model (400 mm in longitudinal direction) with uniform sectional shape from the computed constant domain, and cut end deformation form is computed by performing elastic recovery calculation of the model.

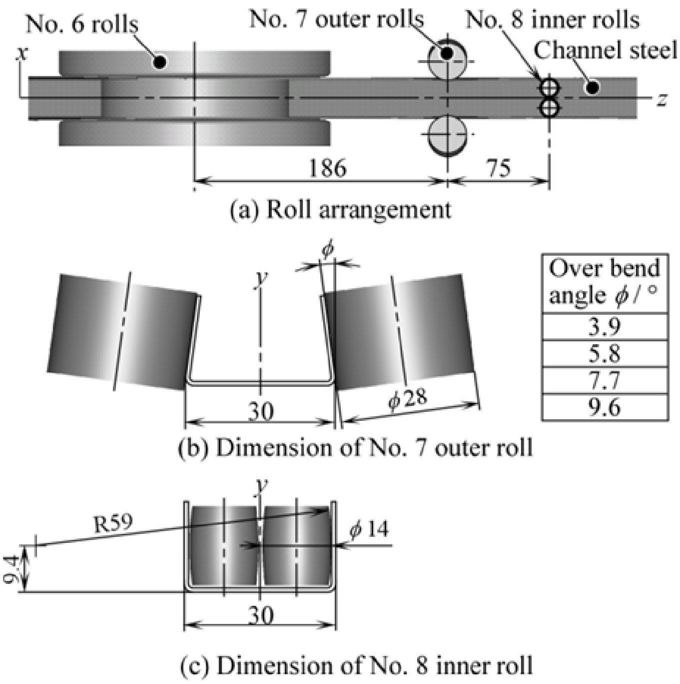

Fig. 4-2 Arrangement and dimenstions of rolls

4.3 Result and Discussion

Fig.2-4 in chapter 2 shows the bend angle variance and the defination of the local coordinate system. 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. The flange angle at downstream for deformation of cut end deformation represent by αF, the flange angle for upstream of is represented by αB. αF－αB is the angle variance. For Fig.4-3 depicted the relation between the overbend angle of No 7 outer roll and the variance of angle value, αF－αB. The difference of bend angle αF－αB is 2.64°,which is the ungiven finishing process of the roll No. 6. Meanwhile, the front end is closing and tail end is opening. The is due to the internal residual shear stress in the work piece. The inner layer is positive while the outer layer is negative.

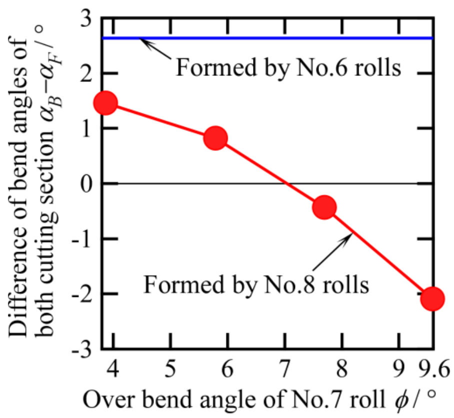

Fig. 4-3 Relationship of difference of bend angles of both cutting section αB－αF and over bend angle of No.7 rollφ, simulation results

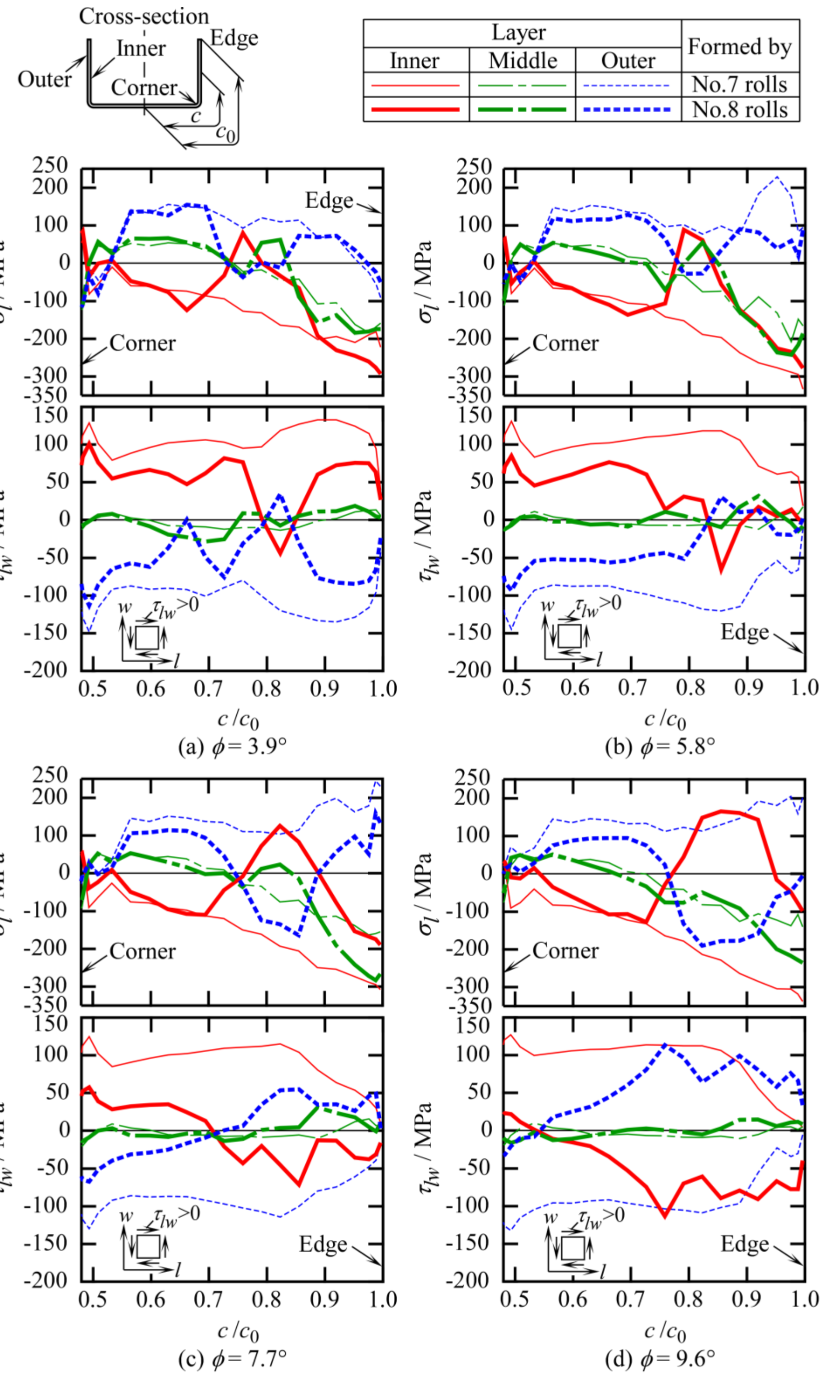

Fig. 4-4 Transversal distribution of residual stress (σ_l : longitudinal stress, τ_{lw} : shear stress in longitudinal-width direction) in flange, simulation results

The release of the inner and outer residual shear stress result on the increase of the over-bend angle of No. 7 outer roll and in the same time, the decrease of it. When $\varphi = 7.7°$, the value of $\alpha F - \alpha B$ is nearly 0. As shown in the fig. 4-4(c), transversal distribution of residual stress in flange for $c/c0 = 0.5 \sim 0.7$ is plus for inner layer and minus for outer layer. For the $c/c0 = 0.7 \sim 1.0$ the outer layer is plus while the inner layer is minus. Thus, as shown in Fig. 4-5, when $c/c0 = 0.5 \sim 0.7$, the front end is closing and tail end is closing. Also, when $c/c0 = 0.7 \sim 1.0$ the front end is opening and tail end is closing. In other words, the opposite direction of cut end deformation occurse between the domain in inner flange corner and the domain for edge parts. This both parts is offset each other make the angle varience $\alpha F - \alpha B$ is nearly 0. Fig. 4-6 illustrate the deformation of channel steel being formed by No.8 rolls and the discussion on the strain rate component. This is the reason of the opposite direction of the shear stress in longitudinal-width direction between the domain of the corner of the flange and the domain of the edge. The convex bending deformation at the center domain of outward flange result of the contact with No.8 inner roll. By the contact of No. 8 inner roll, the bending transformation of the convex occurse outside flange in the central region. It is believe that deformation occurs due to the shear residual stress in the downstream result of the reverse bending deformation through bending line of the radial direction from the roll center position.

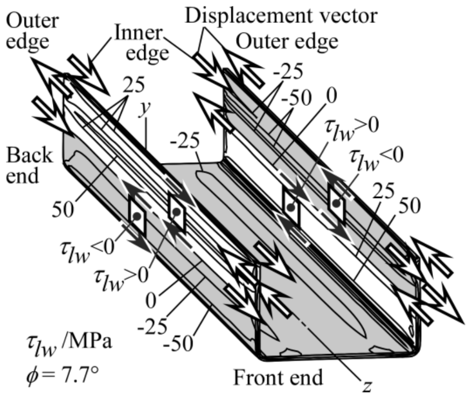

Fig. 4-5 Example of illustration of end deformation occured by relief of $\tau\ lw$ in case of φ = 7.7°

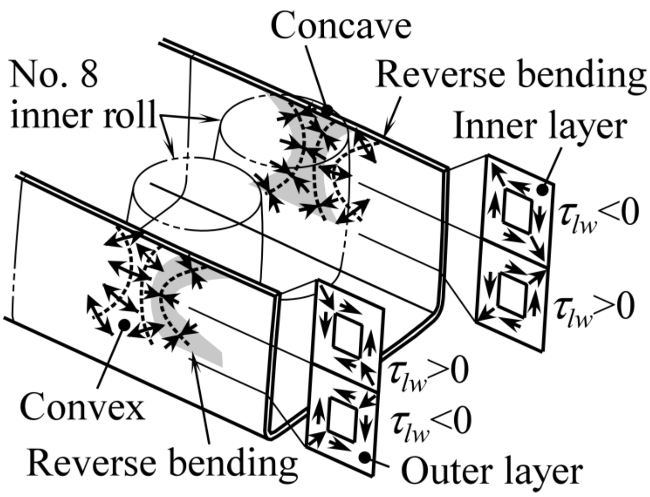

Fig. 4-6 Illustration of channel steel being formed by No 8 rolls and residual stress in case of φ = 7.7°

4.4 Conclusion

1) It is possible to eliminate cut end deformation by the inner roll and outer roll in the finishing porcess.

2) In plane shear residual stress is having opposite direction at the edge side and corner side of the inner plane of flange.

3) Cut end modification of an opposite direction takes place by each, and modification is offset.

Chapter 5 Summary

When hat shape channel steel cut into specified length, the cutting mouth of the product will change by the release of residual stress. This change is generally called cut end deformation. If deformation at cutting mouth of the product is large, the size of a cutting mouth will become out of standard. This will result on joining failure when joining channel steel with other channel steel or channel steel with other components, since deformation arise to the mouth of the channel steel. Therefore, the process of amending the size of the mouth which cut end deformation occurs at front end and back end is needed. This will make production efficiency fall. Moreover, when carrying out flying cut, if a cutting mouth of product changes immediately after cutting, it will lead to cogs breakage. Development of the roll forming method which cut end deformation does not produce from the above is desired. To the best of author knowledge, only few reference in the literature details describe about the mechanism and component of cut end deformation.

In Chapter 2, the cut end deformation of channel steel by roll forming is introduced. 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 aaand 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 an 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.

Chapter 3 describe the cut end deformation of hat channel steel. A three-dimensional finite element simulation was conducted to investigate cut end deformation of hat channel steel and its mechanism. For the steel channel, the top end will close and tail end will open. In contrast, for the hat channel steel, both the top end and the tail end will open. Therefore, this chapter discussed about residual stress occurs on the hat channel steel by simulation results.

In Chapter 4, verification of the method to eliminate cut end deformation by applying a small inner roll at finale tandem of the roll forming process was done. Few method have been reported in order to eliminate cut end deformation, which are over bending method by side rolls without using inner roll. Experiment have been done on over bending method and repeat bending method, but there was no effect at cut end deformation[mihara sensei]. Therefore, in this research, finite element method (FEM) is used and the mechanism of the cut end deformation by inserting inner roll will are discussed.

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