PREVENTION OF WOUND ROLL DEFECT OF COATED WEB

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ABSTRACT

The web which is coated with a coating agent on the surface to add a function is called coated web. This coated web is often made into wound roll to ease handling and storage after coating, and then it is passed to next the manufacturing process to convert to a final product. However, if winding and unwinding tensions are inappropriate, wound roll defect which leads to the function degradation could occur. It is a method to generally adjust the tensions to prevent the wound roll defect. The adjustment has often been through a trial and error process that might lead to loss of time and cost. In order to cut them down, our work is to establish the technology to determine adequate winding and unwinding tensions efficiently through prediction of radial stress and slippage condition within wound roll. In this study, a release paper which is coated on a base paper with a release agent, has an easy peel-off property for pressure-sensitive adhesive (PSA) label is used as an example of coated web. We show one of the efficient methods determining the tensions to prevent the wound roll defect which causes the function degradation that leads trouble during a set of labeling process of PSA label. Additionally, the applicability of the method is showed by experimental verification.

NOMENCLATURE

E_c	elastic modulus of core [Pa]
E_r	elastic modulus of coated web in radial direction [Pa]
E_{rair}	elastic modulus of entrained air layer in radial direction [Pa]
E_{req}	equivalent elastic modulus in radial direction [Pa]
E_θ	elastic modulus of coated web in circumference direction [Pa]
$E_{\theta eq}$	equivalent elastic modulus in the circumference direction [Pa]
F_{cw}	traction force [N]
F_{rl}	peel force [N]
F_{uw}	shear force [N]
h_{air}	thickness of air layer within wound roll [m]

h_{web}	thickness of coated web within wound roll [m]
h_{web0}	initial thickness of coated web [m]
J_r	creep function in radial direction [Pa^{-1}]
J_θ	creep function in circumference direction [Pa^{-1}]
r	roll radius [m]
r_c	core radius [m]
r_M	roll radius at outermost layer [m]
t	elapsed time [s]
T_{uw}	unwinding tension [N/m]
$T_w(r)$	function of winding tension [N/m]
T_{we}	winding tension at outermost layer [N/m]
T_{ws}	initial winding tension [N/m]
W_{web}	width of coated web [m]
ϕ	taper ratio [-]
μ_{eff}	effective friction coefficient
μ_s	static friction coefficient
σ_r	radial stress [Pa]
σ_{r1}	critical radial stress attributed to excessive radial stress [Pa]
σ_{r2}	critical radial stress attributed to slippage [Pa]
σ_{w1}	RMS surface roughness of coated layer surface [m]
σ_{w2}	RMS surface roughness of back surface of coated layer [m]
σ_{ww}	composite RMS surface roughness [m]
τ	retardation time [s]

INTRODUCTION

The web which is coated with a coating agent on the surface to add a function, such as optical property, anti-scratch property and easy peel-off property, is called coated web. The application examples of coated web are information recording media such as Blu-ray disc, mounted component of Flat-Panel Display (FPD) such as liquid crystal display panel and manufacturing assistance component for labeling process of PSA label. The importance of coated web is extremely high.

Coated web is often made into wound roll to ease handling and storage after coating, and then it is passed to the next manufacturing process such as slitting and printing to convert to a final product. However, if winding and unwinding tensions are inappropriate, the function degradation which is attributed to the wound roll defect such as blocking and slippage could occur, and it could lead trouble during the next manufacturing or defect in the product, thus lead to a risk of an economic loss. For these problems, it is the task of pressing urgency to establish the technology to theoretically prevent the wound roll defects [1].

To predict occurrence of wound roll defect theoretically, it is extremely important to estimate the radial stress within wound roll. So far, a large number of studies concentrating on development of winding model have been proposed [2-11]. On the other hand, the study on prevention of wound roll defect has been scarce. As an example of the study, Hashimoto et al. [12] proposed the optimization method of winding tension for preventing wound roll defect, mainly star defect and slippage, based on the optimum design technique.

In this study it is modeled on Hashimoto et al. Release paper for the PSA label is used as an example of coated web, and we show one of the efficient methods determining winding and unwinding tensions to prevent the wound roll defect which causes the function degradation, that leads trouble during a set of labeling process of PSA label. Additionally, the applicability of the method is showed by experimental verification.

RELATIONSHIP BETWEEN FUNCTION DEGRADATION AND TROUBLE

Trouble in Manufacturing and Wound Roll Defect

A release paper is coated on a base paper with a release agent to easily peel off the PSA label, and one of the applicable examples is a manufacturing assistance component on the labeling process of PSA label. This function is called "easy peel-off property" which is generally indicated by peel force that is the required force for peeling off the PSA label from the release paper. The peel force increases than the initial value, which means the function degradation.

Typical labeling process and high-frequency troubles in this process are shown in Fig. 1. First of the process, wound roll of printed PSA label which is laminated with a release paper is unwound, and the PSA label is died cut into predetermined sizes and shapes. Next, the waste part of the PSA label is wound up, which is generally called "waste wind-up" by the producer. Finally, the necessary parts of the PSA label are peeled off from the release paper and labeled on the adherend then the release paper is wound into wound roll. In this process, it could occur "waste wind-up trouble" and "labeling trouble", which are terms to describe the phenomena that the necessary parts are wound up with the waste part and the necessary parts are not peeled off from the release paper, respectively.

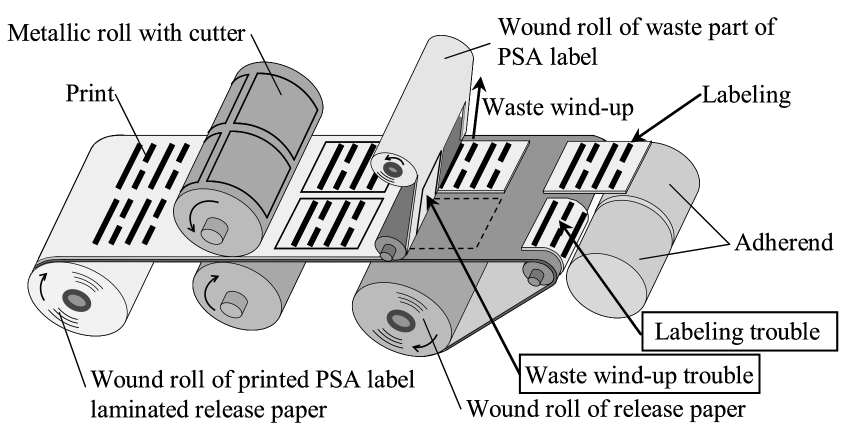


Figure 1 – Schematic of labeling process of PSA label and manufacturing troubles

The waste wind-up trouble could occur if the force which is needed to separate the necessary part from the waste part is greater than the peel force. In order to prevent this trouble, the peel force should be greater than the separation force. On the other hand, labeling trouble could occur if the force that is attributed to the bending stress of the PSA label is less than the peel force. In order to prevent this trouble, the peel force should be less enough to peel easily from the release paper. This relation is trade-off in perspective of the peel force.

The peel force is adjusted by appropriately selecting amongst lots of release agent, and the trade-off problem could be practically satisfied. However, once wound roll defect occurs, the peel force could increase and furthermore the labeling trouble could occur.

Figure 2 shows schematic of a manufacturing process of PSA label. Release paper is made by coating with a release agent on a base paper, and made into wound roll. The release paper is unwound in the next process and coated with PSA on the surface, additionally laminated with a web for printing. Thereafter, the PSA label is printed with character, picture etc on the surface and wound into wound roll, and it is manufactured in the labeling process.

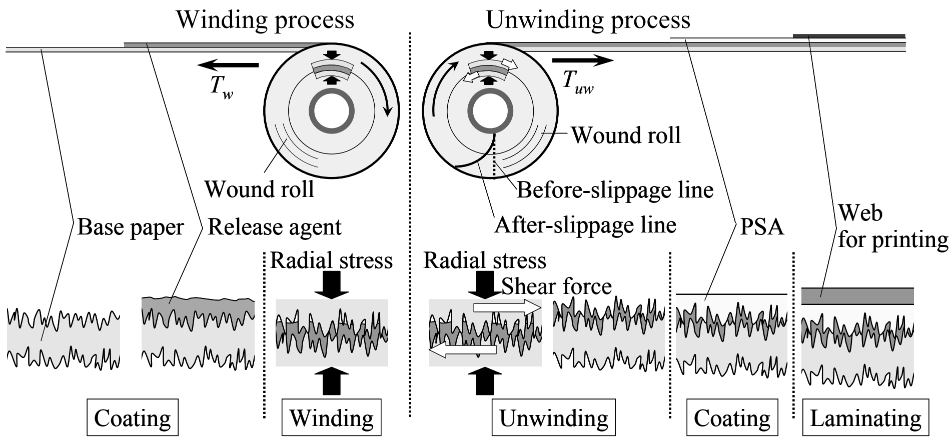


Figure 2 – Schematic of a manufacturing processes of PSA label

In these processes, the release agent layer is pressed with adjacent back surface of base paper by radial stress within the wound roll. If the radial stress is excessive, the surface of the release agent layer could get rougher by deformation that is transferred with the configuration of the base paper surface, which is harder and rougher than the release agent layer and could sink into the layer. Additionally, if shear force which is attributed to the unwinding tension is greater than the traction force between the release papers, slippage in machining direction could occur, and it could cause deformation on the release agent layer by scratching of the convex surface of the base paper, thus, the release agent layer could get rougher. It is estimated that this deformation increases the real contact area between release agent layer and PSA layer, as a result, this leads to increase of peel force.

Confirmation of the Function Degradation

Exploratory experiment is performed to confirm whether the function degradation is attributed to the deformation of the release agent layer. In this experiment, wound roll of release paper with/without slippage are made on the conditions as shown on Table 1 for the physical properties of release paper and Table 2 for processing conditions. Where, the roll with slippage is deliberately unwound until the straight line at the face has gotten bended at all roll radii by slippage after storage at unwinding operation, as shown in Fig. 2. Also, the release agent is selected to be 450mN on peel force, and the surface of the release paper is 0.45μm of the release agent layer and 1.47μm of the back surface of base paper on RMS surface roughness.

The peel force of the release paper of each roll is measured to confirm variation of the easy peel-off property. Figure 3 shows a measuring method of peel force F_{rl}, and the conditions are the width W_{rl} = 50mm, the length L_{rl} = 200mm, peel-off velocity U_{rl} = 300mm/min and length measurement L_{lm} = 100mm. Figure 4 shows the measurement results of peel force to roll radius. According to these results, it is obvious that the peel force tend to increase as it gets closer to the core on both rolls, especially this tendency is noticeable on the roll with slippage. This indicates that the easy peel-off property degrades nearer to the core, and slippage encourages it.

Thickness of web h_{web0}, μm	67.4
Elastic modulus - stress relation in radial direction E_r, Pa $E_r = C_1\sigma^{C2}$	C_1=32400 C_2=0.72
Elastic modulus in circumferential direction E_θ, Pa	9.87×10^9
Set peel force, mN	450
RMS surface roughness of release agent layer σ_{w1}, μm	0.45
RMS surface roughness of back surface of base paper σ_{w2},, μm	1.47
Static friction coefficient μ_s	0.05

Table 1 - Physical properties of release paper

Core radius r_c, mm	50
Outer roll radius r_M, mm	110
Winding velocity, m/min	10
Initial winding tension T_{ws}, N/m	900
Taper ratio ϕ	0.3
Web width W_{web}, m	0.1
Storage time, d	3

Table 2 - Processing conditions

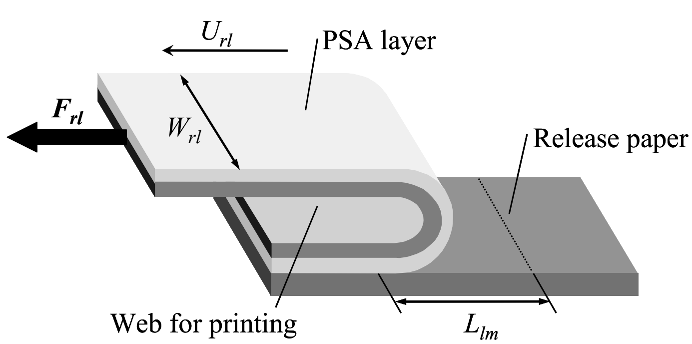


Figure 3 – Measurement method of peel force

In addition, RMS surface roughness is measured on surface of the release agent layer after the peel force measurement. Figure 5 shows the results of the RMS surface roughness to roll radius. From the results, the RMS surface roughness tends to increase as it gets closer to the core on both rolls, and this tendency is noticeable on the roll with slippage, as the peel force. Thus, it is estimated that the deformation is worse when it is closer to the core, and the slippage encourages it.

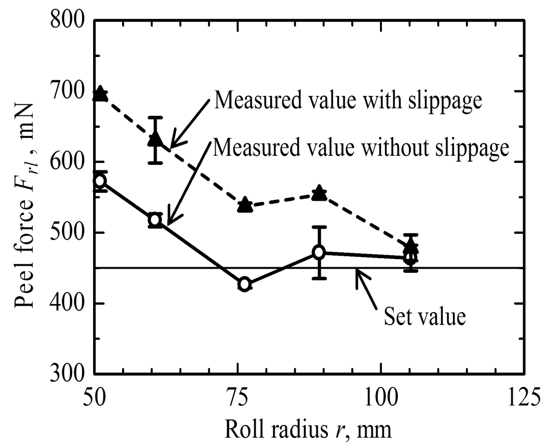


Figure 4 – Measurement results of peel force

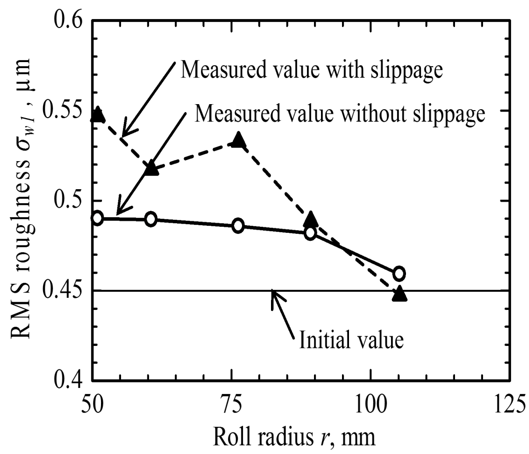


Figure 5 – Measurement results of RMS roughness of

Comparing each of the measurement results, it is apparent that these tendencies to roll radius are similar to each other. Consequently, it is estimated that the degradation of easy peel-off property attributes to the deformation of the release agent layer. In order to prevent the troubles during the labeling process, the release paper must be coated with an appropriate release agent and must be manufactured with adequate winding and unwinding tensions to prevent the wound roll defect which attributes to the function degradation.

ADJUSTMENT METHOD

On setting the winding tension, it is a common-used method to decrease the tension against increasing the roll radius. Generally, the functions of the tension are linear and hyperbolic as shown in Fig. 6. On the other hand, it is constant on unwinding tension. These tension conditions are often determined through a trial and error process that might lead to loss of time and cost. Thus, it has been a task to cut them down.

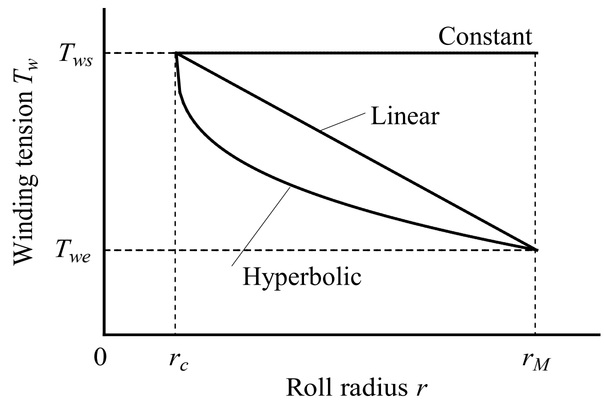


Figure 6 – Conventional functions of winding tension

In this study, radial stress within wound roll is predicted through winding model to theoretically predict occurrence of the wound roll defect. As a first step, roll radial ranges of the occurrence are estimated from the relationship between the radial stress distribution and the measurement values of the peel force. Next, constraint conditions are set by the range, and winding tension and unwinding tension which satisfies the conditions that are determined by applying the winding model. The function of the winding tension is applied as linear, and is determined by the following expression.

$$T_w(r) = T_{ws}\left(1 - (1-\phi)\frac{r - r_c}{r_M - r_c}\right) \quad \{1\}$$

Where, taper ratio ϕ is expressed as:

$$\phi = \frac{T_{we}}{T_{ws}} \quad \{2\}$$

Numerical Model

The effects of web viscoelasticity and air-entrainment within wound roll, significantly affect the radial stress, respectively. We apply the winding model which is based on Hakiel's [7] model for center winding and takes these effects. Additionally, slippage condition is estimated by the equation on the effective friction coefficient between webs, which is formulated by Hashimoto [13].

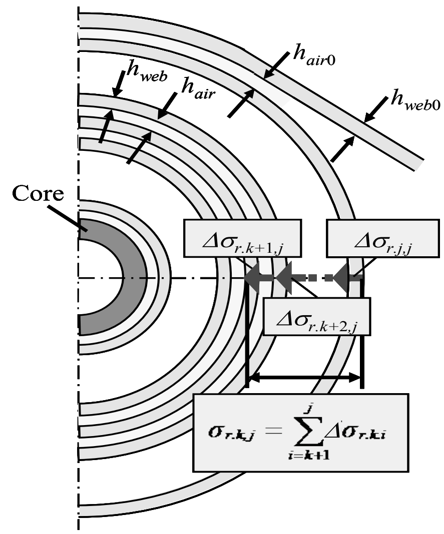


Figure 7 – Numerical model of center winding

Figure 7 shows the numerical model of winding model in this study. The radial stress $\sigma_{r,k,j}$ on lap k in the wound roll with j laps can be expressed as shown in equation {3}.

$$\sigma_{r,k,j} = \sum_{i=k+1}^{j} \Delta\sigma_{r.k.i} \qquad \{3\}$$

The winding equation considering the viscoelastic effect is expressed as follows [9];

$$\int \left[J_\theta \frac{d}{dt'}\left(r^2 \frac{d^2\sigma_r}{dr^2} \right) + 3J_\theta \frac{d}{dt'}\left(r \frac{d\sigma_r}{dr} \right) + \left(J_\theta - J_r \left(\frac{d\sigma_r}{dt'} \right) \right) \right] dt' = 0 \qquad \{4\}$$

Where, J_r and J_θ are creep function defined as the generalized Maxwell model, and are expressed as:

$$J(t - t') = J_0 + \sum_{i=1}^{N} J_i \left(1 - e^{-t/\tau_i} \right) \qquad \{5\}$$

To solve equation {4}, inner and outer boundary conditions follow equations {6} and {7}, respectively.

$$\frac{\sigma_{r.1,j}}{E_c} = \int \left[J_\theta \frac{d}{dt'}\left(r \frac{d\sigma_r}{dr} \right) + J_\theta \frac{d\sigma_r}{dt'} \right] dt' \qquad \{6\}$$

$$\Delta\sigma_{r.j.j} = -\frac{T_w(r)}{r} \qquad \{7\}$$

E_{req} and $E_{\theta eq}$ are calculated by considering equivalent layer combined air layer and web, which are expressed as:

$$E_{req} = \frac{h_{web} + h_{air}}{\frac{h_{web}}{E_r} + \frac{h_{air}}{E_{rair}}} \quad \{8\}$$

$$E_{\theta eq} = \frac{h_{web}}{h_{web} + h_{air}} E_\theta \quad \{9\}$$

Thus, creep function J_{req} and $J_{\theta eq}$ on the equivalent layer are given, by

$$J_{req} = \frac{1}{E_{req}} + \sum_{i=1}^{N} J_{ri}\left(1 - e^{-t/\tau_{ri}}\right) \quad \{10\}$$

$$J_{\theta eq} = \frac{h_{web} + h_{air}}{h_{web}}\left(\frac{1}{E_\theta} + \sum_{i=1}^{N} J_{\theta i}\left(1 - e^{-t/\tau_{\theta i}}\right)\right) \quad \{11\}$$

J_r and J_θ showed above are replaced to J_{req} and $J_{\theta eq}$, respectively. Using these equations, the radial stress can be predicted with taking the effects of viscoelasticity and air-entrainment.

The slippage at unwinding operation could occur if traction force between webs was less than the shear force which is attributed to the unwinding tension. In order to calculate the traction force, it is needed to estimate the effective friction coefficient μ_{eff} between webs. In this study, it is estimated by the following relation [13].

$$\mu_{eff} = \begin{cases} \mu_s & \left(h_{air} < \sigma_{ww}\right) \\ \frac{\mu_s}{2}\left(3 - \frac{h_{air}}{\sigma_{ww}}\right) & \left(\sigma_{ww} \le h_{air} \le 3\sigma_{ww}\right) \\ 0 & \left(h_{air} > 3\sigma_{ww}\right) \end{cases} \quad \{12\}$$

Where σ_{ww} means the composite RMS surface roughness of web defined by:

$$\sigma_{ww} = \sqrt{\sigma_{w1}^{\ 2} + \sigma_{w2}^{\ 2}} \quad \{13\}$$

Subscripts w1 and w2 mean RMS surface roughness of coated layer surface and web surface opposite coated layer surface, respectively. The traction force F_{cw} is calculated by

$$F_{cw} = 2\pi r W_{web} \mu_{eff} \left|\sigma_r\right| \quad \{14\}$$

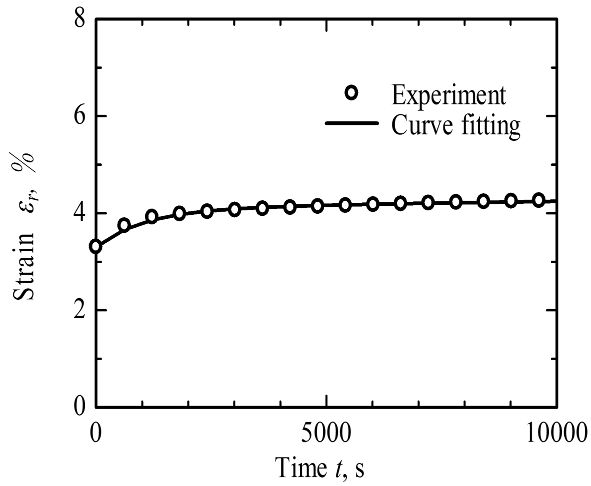
Consequently, the slippage could occur if it is satisfied following inequality equation.

$$F_{cw} < F_{uw} = T_{uw} W_{web} \frac{r_M}{r} \quad \{15\}$$

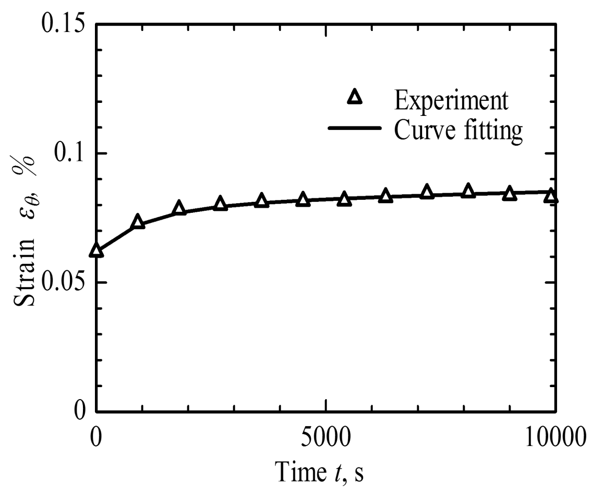
Where, the constants of the creep functions as shown equation {10} and {11} must be experimentally determined in order to predict the radial stress. Figure 8 shows measurement results of strain to time on the release paper at constant stress condition in radial and circumference directions. The constants are determined by approximation as follows:

$$J_{req} = \frac{1}{E_{req}} + 5.31 \times 10^{-11}\left(1 - e^{-t/10^3}\right) + 4.22 \times 10^{-11}\left(1 - e^{-t/10^4}\right) \qquad \{16\}$$

$$J_{\theta eq} = \frac{h_{web} + h_{air}}{h_{web}}\left(\frac{1}{E_\theta} + 1.18 \times 10^{-8}\left(1 - e^{-t/10^3}\right) + 1.05 \times 10^{-8}\left(1 - e^{-t/10^4}\right)\right) \qquad \{17\}$$



(a) Radial direction



(b) Circumferential direction

Figure 8 – Viscoelastic strain of the release paper

Setting of Constraint Conditions

Considering the measurement results of peel force on exploratory experiment, setting method of the constraint conditions is specifically showed. Where there are wide varieties of machinery and processing conditions for labeling process, thus, the peel force which induces the trouble differs in many cases. However, the peel force must be previously known. In this study, the adjustment is carried out on empirically-deduced conditions that waste wind-up trouble occurs less than 400mN and labeling trouble occurs greater than 500mN.

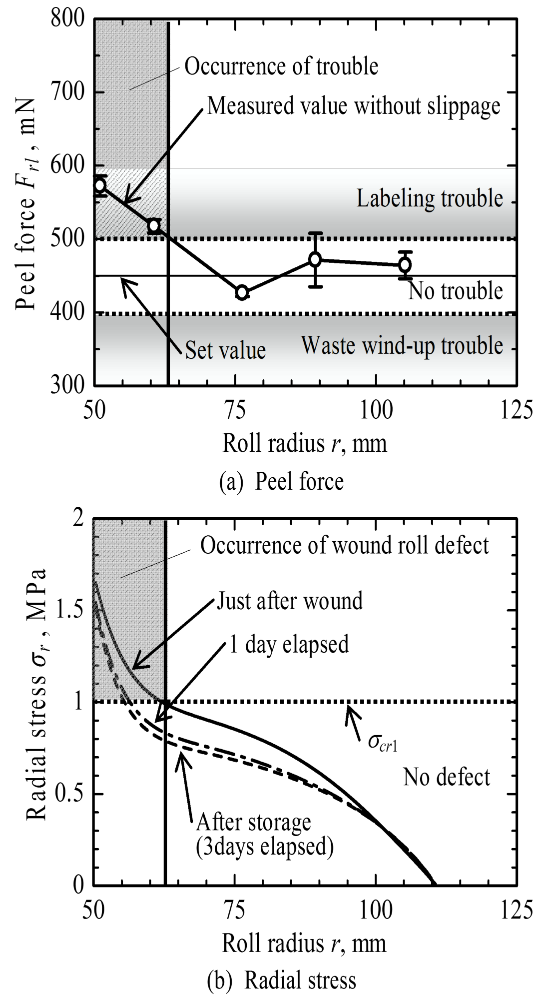


Figure 9 – In-roll distributions on wound roll without slippage

First, it is considered on the wound roll defect attributed to the excessive radial stress. Figure 9 (a) shows the measurement result of peel force without slippage as shown in Fig.4 and the trouble-occurrence areas. Comparing them, there are no the measurement values in the area less than 400mN, and it is estimated that waste wind-up trouble could not occur. However, considering the measurement values which are greater than 500mN, labeling trouble could occur in the range of 50mm to 63mm on roll radius. Where, the measurement values which are out of the waste wind-up trouble area show that selection of release agent is appropriate as mentioned above.

Figure 9 (b) which shows analysis results of the radial stress, indicates that the radial stress varied over time during storage. The radial stress is highest at the innermost layer, decreases to roll radius and becomes close to zero at the outermost layer. This decreasing degree is especially high near the core. Furthermore, the radial stress just after wound is the highest, decreases over time and reaches almost saturation value after the storage at the same roll radius. From these results, it is estimated that the wound roll defect attributed to the radial stress tends to occur near the core and the just-after-wound radial stress significantly affects it.

Consequently, the just-after-wound radial stress is greater than 1.0MPa, which corresponds to the roll-radial range predicted occurrence of labeling trouble, thus critical radial stress attributed to excessive radial stress σ_{cr1} is determined 1.0MPa. The constraint condition to determine the winding tension T_w to prevent the wound roll defect is set as the following relational equation.

$$\sigma_{r,just-after-wound} < \sigma_{cr1} \qquad \{18\}$$

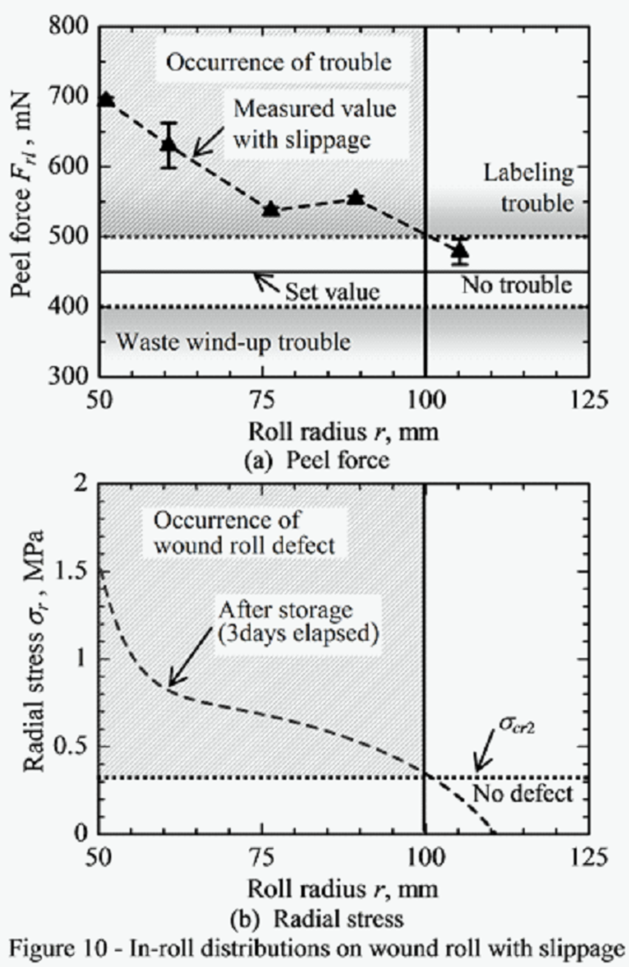


Figure 10 - In-roll distributions on wound roll with slippage

Next, it is considered on the wound roll defect attributed to the slippage. Figure 10 (a) shows the measurement result of peel force with slippage as shown in Fig.4 and the trouble-occurrence areas. According to this result, the waste wind-up trouble could not occur, but labeling trouble could widely occur from 50mm to 100mm.

Where, the slippage is made after storage. Therefore, it is estimated that after-stored radial stress affects the wound roll defect which attributes to the slippage. As the excessive radial stress, the after-storage radial stress which corresponds to the roll-radial range that is predicted occurrence of the labeling trouble is greater than 0.3MPa as shown in Fig. 10 (b), the critical radial stress attributed to slippage σ_{cr2} is determined 0.3MPa. The constraint condition to determine the unwinding tension T_{uw} to prevent the wound roll defect is set as shown in equation {19}.

$$\sigma_{r,after-storage} < \sigma_{cr2} \tag{19}$$

<u>Procedure of the adjustment</u>

Figure 11 shows procedure for the adjustment of winding and unwinding tensions to prevent the wound roll defect. First, the wound rolls with/without slippage are experimentally made by arbitrary winding tension. After unwinding the rolls, peel forces are measured at predetermined roll radii, and the trouble-occurrence areas of each roll are estimated by the results of the peel force. Next, the radial stress distributions of each roll are predicted by the winding model. Furthermore, the constraint conditions to determine the tensions are set by considering the relationship between the radial stress distributions and the trouble-occurrence areas. Finally, winding and unwinding tensions which satisfy the constraint conditions are respectively explored and determined through the winding model.

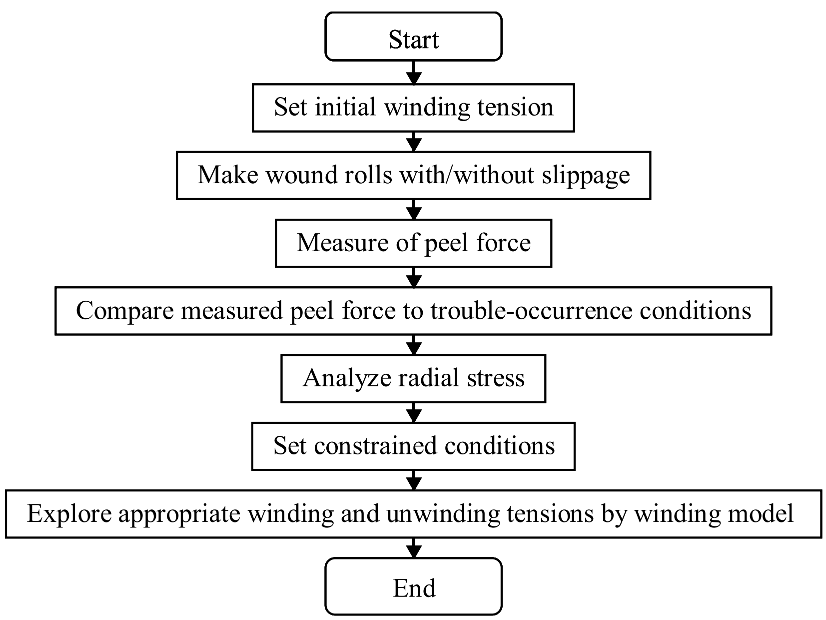


Figure 11 – Flowchart of the procedure for adjustment of winding and unwinding tensions

RESULTS AND DISCUSSIONS

The applicability of the adjustment method will be experimentally verified. In this verification experiment, the release paper and the processing conditions are applied as the exploratory experiment except for winding and unwinding tensions.

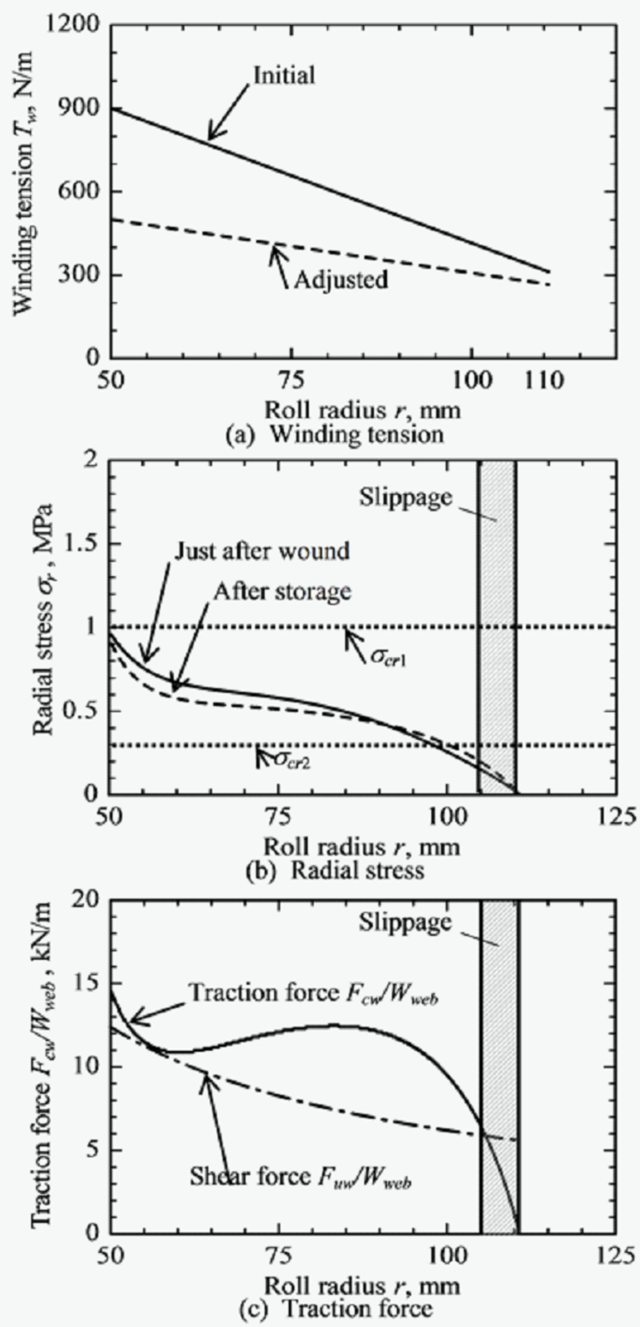


Figure 12 – In-roll distributions on the adjusted condition

From the adjustment result which is determined through the procedure, the adjustment conditions are obtained with winding tension T_w in 500N/m, taper ratio ϕ in 0.5 and unwinding tension in less than 600N/m. Figure 12 (a) shows that the adjusted winding tension, (b) and (c) show the analysis results of the radial stress indicated to determine the adjustment conditions and traction force to predict the slippage range by the unwinding tension, respectively.

The analysis result shows that the just-after-wound radial stress by the adjusted winding tension is less than 1.0MPa at all range of roll radius, and this satisfies the equation {18} of constraint conditions. From the result of the traction force which is calculated with after-storage radial stress, slippage could occur if traction force F_{cw} is less than shear force F_{uw} as shown in equation {15}, and it is estimated that the largest slippage range is from 105mm to 110mm on the adjusted unwinding tension. In this range, the after-stored radial stress is less than 0.3MPa, and this satisfies the equation {19}.

Figure 13 shows the measurement result of peel force on the adjustment conditions and the trouble-occurrence areas. This measurement result shows that all of the measurement value is out off the areas, thus the wound roll defect does not occur.

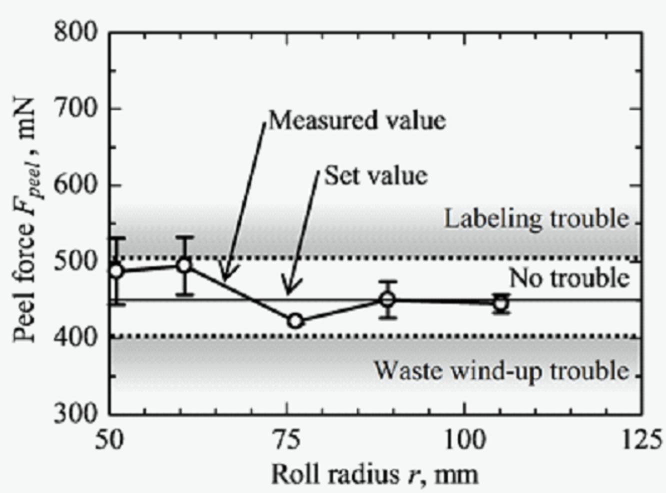


Figure 13 – Peel force on verification experiment

Winding and unwinding tensions to prevent the wound roll defect of coated web are efficiently determined without a trial and error process by the method we suggested above. Additionally, the applicability of the method is showed by experimental verification.

CONCLUSION

In this study, a release paper for PSA label is used as an example of coated web. And we show one of the efficient methods to determine winding and unwinding tensions to prevent the wound roll defect which causes the function degradation that leads troubles during a set of labeling process of PSA label. Additionally, the applicability of the method is showed by experimental verification. Therefore, the method could cut loss of time and cost compared to the traditional method.

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Prevention of Wound Roll Defects on Coated Webs	**T. Kanda**[1]**, S. Akemine**[1]**, & H. Hashimoto**[2], [1]LINTEC Corporation, [2]Tokai University, JAPAN

Name & Affiliation	**Comment**
Hiromu Hashimoto, Tokai University	Mr. Kanda's company manufactures many kinds of coated webs. This company was suffering serious economic losses due to the wound roll defect shown in my presentation. After the prevention method proposed in this work was employed, we were successful in reducing these losses.
Name & Affiliation	**Question**
Jan Erik Olsen, SINTEF Materials and Chemistry	I have a question about your comments. Are you talking about a simple web or a complex web? At the last conference, there was a lot of talk about the flexible display industry. Could this method be applied those kind of webs?
Name & Affiliation	**Answer**
Hiromu Hashimoto, Tokai University	Yes. This method can be applied to the production of flexible displays.
Name & Affiliation	**Question**
Dilwyn Jones, Emral Ltd.	The winding model you were using was a complex model incorporating viscoelasticity and air entrainment. Do you think you could have gotten similar results with a more basic winding model?
Name & Affiliation	**Answer**
Hiromu Hashimoto, Tokai University	It depends on the physical properties of the web involved. In some cases, the viscoelasticity and air entrainment have insignificant effect on the wound roll. In the case treated in this paper, these effects cannot be neglected, so we applied a winding model including viscoelasticity and air entrainment.