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Effect of Radial Stress on the Adhesive Force of a Wound Roll in Industrial Roll-to-Roll Manufacturing System

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There is a correlation between the radial stress and the adhesive force of a wound roll in an industrial scale roll-to-roll manufacturing system. The system considered in this study is used for the fabrication of wide-width (2235 mm) adhesive film of 30 μm thickness. This manufactured adhesive film is used for protection in one manufacturing step of a liquid crystal display line. The radial stress, which is measured in this study using force sensitive resistor sensors, is a major factor influencing the degradation of adhesive force. The adhesive forces were measured based on the tape method with the direct pull-off test. It is confirmed that the radial stress has an inversely proportional effect on the adhesive forces of the film. To improve the resulting adhesive value of the film, adjustments to operating tension and taper value are employed. Statistical analysis shows that low tension conditions result in less adhesive deviation, and that low taper values at high tensions can reduce the deviation of adhesive forces. The tension control guidelines contribute to an improvement in mass production of roll type adhesive film products used in displays and other applications.

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NOMENCLATURE

σ_w = web stress in winding
σ_0 = initial web stress
taper = decrement of the taper tension
r = dimensionless roll radius ratio (i.e., the radius divided the core radius)
R = current radius of the roll
ψ = volume of adhesive tape lost
k_w = coefficient of the adhesive tape
F_L = total load normal to the adhesive tape
v = distance the adhesive is dragged across the substrate surface
H = hardness of the adhesive tape

1. Introduction

Web handling is a fundamental technology in roll-to-roll platforms. In this application, a web is defined as a long film that has a relatively thin thickness compared to its width, which can be wound into a roll shape, e.g., plastic film,[1] metal foil,[2] paper[3] or woven fabric.[4] In the film manufacturing process, the web must have a uniform thickness and width, and must be transported stably to the winding section to result in a good final product. Recently, such web based roll-to-roll platforms have been considered to be an innovative future technology for many production applications such as solar cells,[5] batteries,[6] lighting,[7] electronic circuits,[8] and sensors.[9]

Web handling technology is based on precise tension control. Current motor technology is very precise and has high resolution, so there is no fundamental problem with providing appropriate speed control. However, tension control can be very challenging as it operates on a flexible linked system, which means the web is flexible and the interaction between the web and the rolls must be considered.[10] Past research has attempted tension control using methods that can be subdivided into lateral control,[11] register control,[12] dancer control,[13] and unwinding and rewinding control.[14]

In the area of tension control, rewinding control is one of the most researched technologies due to its direct connection to the quality of the final product. The key issue in rewinding control is avoiding defects due to irregular radial stress in the wound roll such as starring,

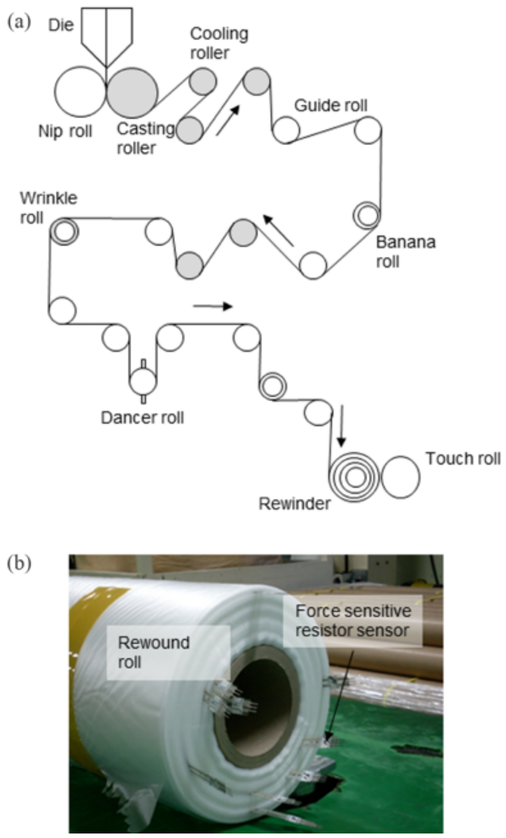

Fig. 1 (a) Schematic of an industrial roll-to-roll film fabrication system, (b) the final product as a rewound roll, showing mounted force sensitive resistor sensors

telescoping, etc.[13] These defects can be eliminated by setting the proper taper profile. The taper profile is a set value of tension along the radius of wound roll. Since the winding rolls have radial stress due to high accumulated web gravity, hoop stress, and bending stress, the winding tension is set to be the largest at the beginning and decrease as the radius of the roll increases.[15] There has been a great deal of research into the implementation and optimization of the taper tension profile. Benson et al. developed a new model for predicting the internal loads in a wound roll.[16] Good et al. presented new boundary conditions to calculate the inertial stress of a roll with the presence of rollers.[17] Lee et al. investigated an advanced taper tension profile by suggesting a hybrid model development using existing linear and hyperbolic profiles.[13] Furthermore, Lee et al. developed an advanced radial stress model in a recent report that considered the gravitational and bending stress in the wound roll.[15]

Previous studies have attempted to reduce the apparent defects in wound rolls of many types, but adhesive films have the additional mission of maintaining the adhesion functions of the wound material. Adhesive films have been adopted for the encapsulation of solar cell products,[5] multi-layer circuit boards,[18] and liquid-crystal displays.[19] The uniform coating of the adhesive layer onto the flexible film is important, and the good winding of long films is an important component of the process to be considered at the end of film production.[20]

In this work, we determine the effect of radial stress on the adhesive force of wound adhesive films. An industrial scale roll-to-roll system was used to confirm the practical winding behavior of the actual product. Using this system, appropriate operating parameters within the practical operation ranges of roll-to-roll systems, namely operating tension and taper value, were experimentally analyzed for their ability to improve the adhesive force of the film in the wound roll.

2. Materials and Method

The roll-to-roll film manufacturing system is composed of casting, measurement, take off, and winding components. Fig. 1(a) shows a simplified schematic of the roll-to-roll manufacturing system used in this study. The major components of the system are the extrusion die for the adhesive film material, the nip roll, casting roll, cooling roller, guide roll, banana roll, wrinkle roll, dancer roll, rewinding roller, and touch roll. The designations of “roller” and “roll” indicate motor-driven and idly driven rotary components, respectively. The fabricated adhesive film had a width of 2235 mm and a thickness of 30 ± 5 µm, shown in Fig. 1(b). The operating velocity, operating tension, winding diameter, and taper value were 120 m/min, 9.5-20 N, 180 mm, and 0-20%, respectively.

Operating tension and taper value are experimental parameters that affect the winding performance of the roll.[14] Operating tension can be defined as the tension applied to the entire web resulting from the speed difference between the preceding infeeder and the master speed roller. Here we consider the linear taper tension profile, which is commonly used in industrial applications, and can be represented as follows in Eq. (1):[21]

$$\sigma_w(r) = \sigma_0\left[1-\left(\frac{taper}{100}\right)\frac{(r-1)}{(R-1)}\right] \tag{1}$$

For the control of taper tension in the system, the set value is assigned to the motor drive (590 Series, Eurotherm Drive Inc., UK), and controls the electro pneumatic (E/P) converter employed to control the pressure in the pneumatic cylinder of the dancer system (see a schematic of the taper tension control system in Fig. S1). The motor drive is capable of control in the range of -5 V to 5 V for a taper value from -50% to +50%.

For measuring the radial stress, a force sensitive resistor sensor (Flexiforce A201, Tekscan, Inc., USA) was used. A sensor was mounted at the radius ratios r of 1.04, 1.07, 1.13, 1.2, 1.25, 1.3, 1.6, 1.86, 2.07, and 2.28, as shown in Fig. 1(b). The measurement ranges, linearity (error), repeatability, hysteresis, drift, response time, and operating temperature of the sensor are 4.4-445 N, ±3%, ±2.5%, 4.5%, 5%, 5 µs, and -40°C~+60°C, respectively.

The manufactured film in this study is a protective adhesive film used in the liquid crystal display industry. The film is used during the manufacturing process of display products, which must be accessible through attachment and detachment of components with sufficient adhesion. However, as the roll winds and the radius increases, the adhesive force is not uniform due to the change in radial stress distribution. The adhesion of the film was determined by the tape method with the direct pull-off test,[22] and its correlation with the change in radial stress was verified. The reliability of the adhesion values was verified by comparative measurement of the roll left and right. The

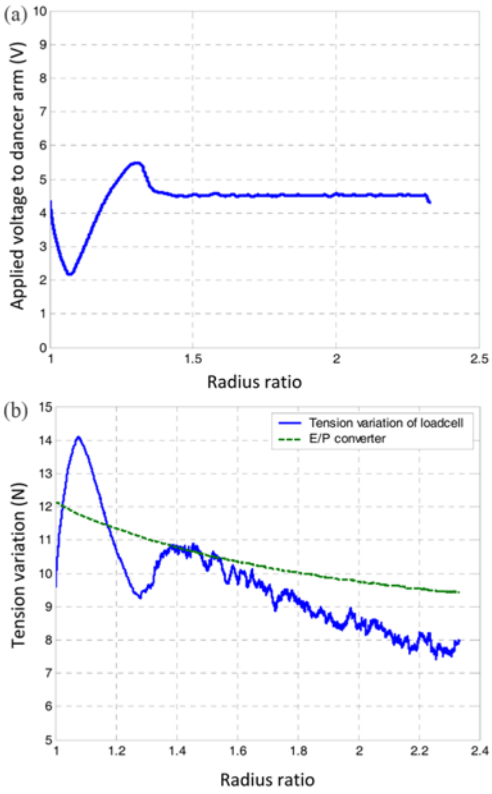

Fig. 2 (a) Dancer signal vs. radius ratio (b) tension variation vs. radius ratio, measured by load cell and E/P conversion signal

results are shown in Table S1, and the difference is not large.

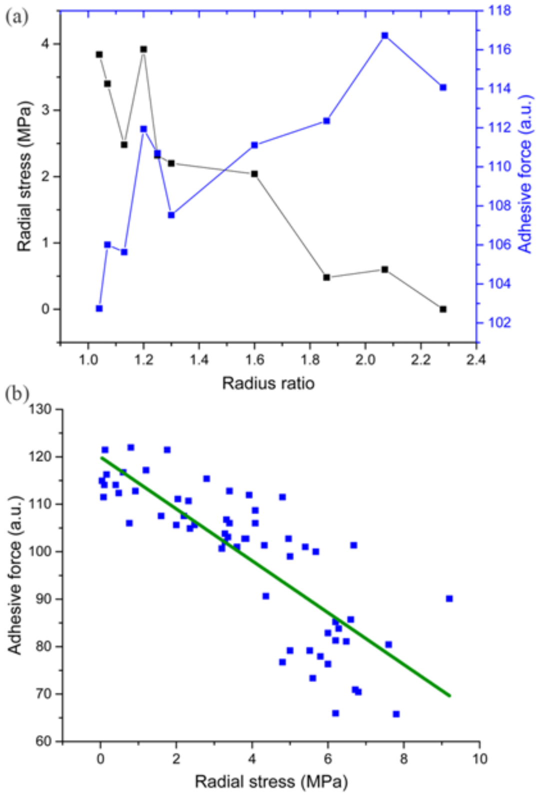

Fig. 3 (a) Radial stress and adhesive force in a wound roll as the radius ratio changes under an operating tension of 10 N and a taper value of 10% (b) inversely proportional relationship between adhesion force and radial stress in the entire experimental set (R-square: 67.2%)

3. Results and Discussion

Fig. 2 shows the web tension control data of the roll-to-roll system with an operating tension of 10 N and a taper value of 10%. The dancer angle is changed by an E/P converted signal from the motor drive controller. The applied voltage on the dancer varied from 2.2 to 5.4 V, and stabilized at a radius ratio of 1.37, as shown in Fig. 2(a). The change in dancer angle equated to a tension variation from 9.3 to 14.1 N, which continued to change despite the stability of the E/P signal, as shown in Fig. 2(b). After E/P signal stabilization at a radius ratio of 1.37, the tension exhibits steady linear declivity (see Figs. S2-S6 for other experimental results under different conditions).

The linear decrement of tension in the winding section affects the radial stress, which was measured by force sensitive resistor sensors, as shown in Fig. 3(a). The radial stress was distributed from 3.92 to 0.05 MPa for a measured adhesive force from 102.7 to 116. Interestingly, the values of radial stress and adhesive force are inversely proportional to each other. This phenomenon was observed in all experimental cases, as shown in Fig. 3(b). Adhesive strength tended to decrease from a maximum of 121.9 to a minimum of 65.7 while radial stress increased from 0.04 to 9.2 MPa. In this experiment, there was no effect due to chemical factors on the adhesive strength of the film, so the degradation of adhesive was closely related to these changes in mechanical factors. This inversely proportional relationship could be explained by the mechanical wear of adhesive films. The following equation presents Archard's law of adhesive wear,[23]

$$\psi = k_w \frac{F_L v}{H} \tag{2}$$

Most of the wear on an adhesive is generated from shear force during dragging with a high v, but F_L also contributes to the degradation of an adhesive as a result of significant radial stress in this case. In the winding process, there are three main forces: tension on the web, shear force in the direction tangential to the wound roll (winding direction), and radial stress. F_L in the inside of the roll is higher than that outside of the roll, with a difference in radial stress of about 4 MPa. If the values of k_w, v, and H are fixed in the process, Ψ-differences between the inside and outside of the wound roll are linear in relationship due to the linearity of radial stress, as shown in Fig. 3(b). Moreover, residual stress always remains in the center of wound rolls which can significantly affect the radial stress during long storage durations.[13,24]

It is confirmed that the adhesive force of a film is determined by the radial stress on the wound roll. A statistical analysis was conducted with operating tension and taper value as input and adhesive force as output. The results of the analysis of variance, showing degree of freedom, sum of squares, mean square, and F value are listed in Table 1. The results indicate that the operating tension is the most significant

Table 1 Results of the analysis of variance of the measured adhesive forces

	Degree of freedom	Sum of squares	Mean square	F value	P value
Operating tension	2	4750.819	2375.409	16.02959	3.4310^{-6}
Taper value	3	438.2352	146.0784	0.98576	0.40643
Error	54	8002.207	148.189	-	-
Corrected total	59	14147.5	-	-	-

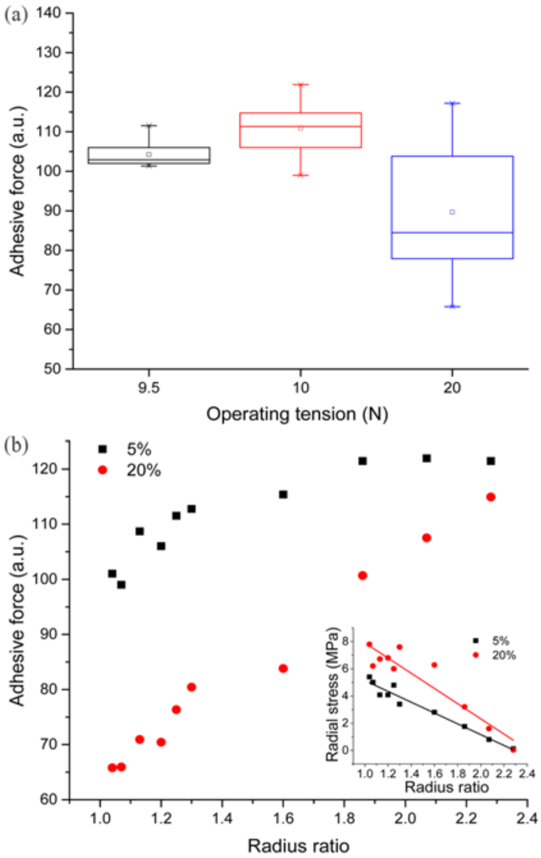

Fig. 4 (a) Box plot of adhesive force for different operating tension settings (b) adhesive force change with radius ratio for taper tensions of 5% and 20% in the presence of a 20 N operating tension (inset: radial stress for each taper value plotted against radius ratio)

factor on the adhesive force of a wound roll of film. It is also shown in Fig. 4(a) that operating tensions of 9.5, 10, and 20 N correspond to a standard deviation of adhesive forces of 3.16, 6.54, and 16.1, respectively. A high operating tension leads to high radial stress, which causes a degradation of adhesive force of 89.7 (average value). Furthermore, a high standard deviation of 16.1 signifies the nonuniformity of adhesive force along the wound distance of the roll due to a drastic radial stress distribution. In this situation, the taper control could be a solution to the nonuniformity of adhesive forces. Fig. 4(b) shows the adhesive forces for different taper values of 5% and 20% in the presence of a 20 N operating tension. The 5% taper exhibited a standard deviation of 22.9 within a range of 99-121.9 and the 20% taper exhibited a standard deviation of 49.1 within a range of 65.8-114.9. These differences come from the radial stress decrement of each taper value, as shown in the inset of Fig. 4(b). The radial stress distributions for the taper values of 5% and 20% were 0.04-7.8 MPa and 0.12-5.4 MPa, respectively. As mentioned previously, relatively low radial stress values and low standard deviations affected small changes in the adhesive force. The simulation results based on the Burns model[24] also show that the lower radial stress distribution is determined by the lower taper value (see Fig. S7 for simulation results for radial stress with different taper values). Note that some previous studies have prevented the telescoping or starring of rolls by drastically reducing radial stress, but this study indicates that such rapid radial stress reduction (slope change) results in a sharp decrease in adhesion and should be avoided.

4. Conclusion

In this paper, the effect of radial stress on the adhesion characteristics of an adhesive roll is presented. An industrial roll-to-roll manufacturing system was employed to fabricate adhesive films for a liquid crystal display product. The various tension and taper value settings evaluated were applied by a motor drive and E/P converter, and a linear taper tension profile was used for the experiments. The results show that the different operating tension and taper values can be used to determine the radial stress profile in the wound rolls. Moreover, the radial stress was found to be inversely proportional to the adhesive force of the film (which was measured by force sensitive resistor sensors), i.e., the adhesive force declines as the radial stress is increased. This degradation of adhesive force is predicted to be caused by mechanical wear on the adhesives, and can be improved by optimizing the process conditions, operating tension, and taper value. Using a statistical analysis, the operating tension is shown to more significantly affect the adhesive forces than any other factor. In conditions of low operating tension, the deviation of adhesive force can be minimized. Additionally, the taper value can be reduced to reduce the deviation of adhesive force by minimizing radial stress deviations. The conclusions of this study contribute to an improvement in film adhesion and can be applied to lower the defect rate of roll type adhesive film products used in displays and other applications.

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