Rolled plastic film damage simulation considering surface roughness useful for greenhouse roof automatic ventilation

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Abstract. Greenhouses are capable of producing a variety of high-value crops year-round. A novel Japanese greenhouse design is gaining popularity because of its automated rolled-up ventilation system that is integrated into the roof. However, due to the frequent movement of the roll-up system, the plastic film deteriorates rapidly and typically lasts for only three or four months. In order to better understand the film deterioration, we studied the mechanics involved at the point of contact between the film and the metal greenhouse frame. We found that film deformation and failure were closely related to stretching and creasing, and these processes were observed at the microscope level. In this paper, the plastic film damage was investigated through the rolling contact analysis focusing on the pipe surface roughness. We found that at the inside film surface the larger strain is caused by the pipe surface roughness. This larger strain generates the wave deformation of the film, crease and line scar whose number increases with increasing the roughness of the arch pipe. The effects of pipe coating and perforated film are discussed to prevent the film damage.

1. Introduction

A novel greenhouse is being used recently since automated rolled-up ventilation system is contained in into the roof to control the temperature. A variety of high-value crops can be produced year-round by providing most suitable temperature. The fully opening automatically ventilated greenhouse can control the inside temperature by automatically rolling up and rolling down the plastic film from the gutter toward the ridge. Until now although partially- opening type green houses are widely used, full-opening type greenhouse are not because the plastic film deteriorates rapidly due to the frequent movement of the roll-up system. It has been requested to investigate the plastic film damage mechanism and to find out how to prevent the damage under rolling contact loading. The several contact stresses, and the rolling contact solutions of elastic film sandwiched between two parallel cylinders were provided by Johnson [1]. Regarding rolling of polypropylene sheet, Nakamura and Takasu investigated the mechanical properties and molecular orientation in the rolled sheets by tensile tests, sonic propagation method, birefringence, and dynamic viscoelastic measurements [2]. Instead of between two parallel pipes, the film deformation was considered between two orthogonal pipes considering rolled-up ventilation [3].

Noda et al summarized the film damage process of automated rolled-up ventilation in the following way [3]. Damage begins on the inside film surface, contacting the greenhouse frame pipes. Compressive rolling stress induces stretching zones with indentations that lead to creases. Eventually, the creases fold over and develop line scars which are perpendicular to the rolling direction. Since the

film thickness reduction causes elongation and creasing of the film, these deformations are closely related to film damage [4]. Noda et al also found that temperature severely influences the damage. At 70°C, which are measured pipe surface temperature of greenhouse pipes during the summer, the rolling contact experiment inflicts line scars on the plastic film [4].

However, those previous studies did not consider the pipe surface roughness, which may affect the creation of line scars significantly and therefore the film damage process has not been completely explained yet. In this paper, therefore, different surface roughness will be introduced on the arch pipe and the number of line scar will be studied experimentally for the film sandwiched between the arch pipe and the rolling pipe. The simulation will be also performed by changing the model surface roughness. Moreover, since perforated films are sometimes used to reduce the inside temperature, the effect of holes on the film damage will be also studied. To prevent the film damage contributes the widely use of automated ventilation system.

2. Rolling contact experimental and analytical results considering pipe surface roughness

Figure 1 shows the developed rolling contact machine with which the damage to greenhouse films was investigated [4]. In this apparatus, the pipe that rolls over the film is pulled across and turns under the friction between itself and the film. Each support pipe carries an average load of 15 N. However, the actual load becomes larger when the support pipe deflects. Greenhouse roofs are also subject to another force provided by hard wind and rain and exerted by the holding strap. Therefore, we should assume that loads up to 75 N could be applied to the support pipe.
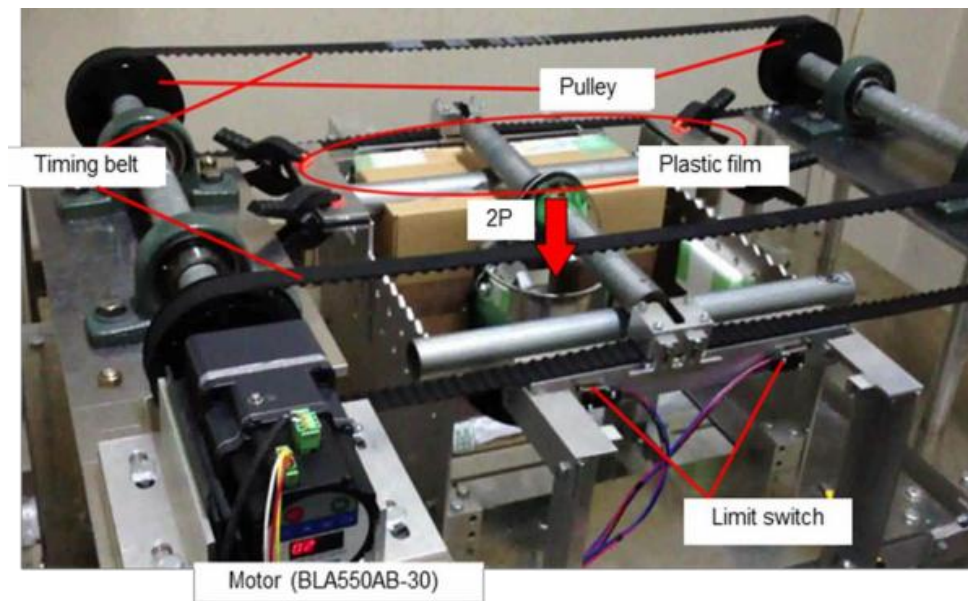

Figure 1. Rolling contact machine to investigate plastic film damage.

Figure 2 shows the number of line scar /cm ($n_{\text{line scar}}$) observed during the rolling contact experiment by changing the support pipe surface roughness R_y. It is seen that with increasing roughness of the support pipe R_y, the number of line scar /cm ($n_{\text{line scar}}$) increases independent of the pipe diameter. The number of line scar /cm ($n_{\text{line scar}}$) can be expressed as the following approximate equation.

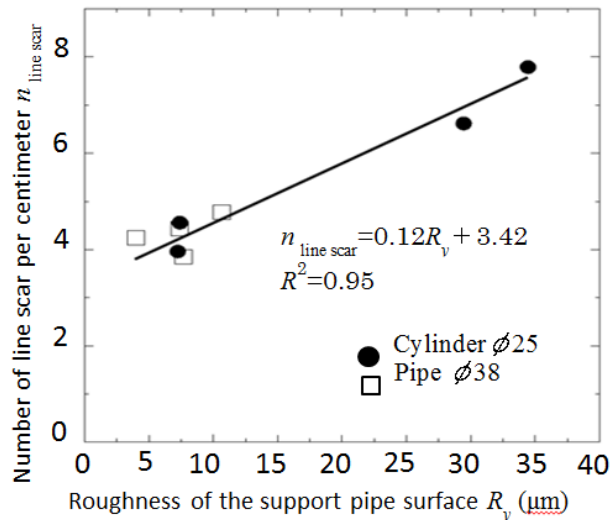$$n_{\text{line scar}} = 0.12 R_y + 3.42 \quad (R^2 = 0.95). \tag{1}$$

Figure 2. Relationship between the number of line scar /cm and the surface roughness of the support pipe R_y.

The previous FEM study showed that the number of line scar is controlled by the film strain assuming smooth pipe surface [3]. In this study, the effect of surface roughness will be studied by applying the finite element method (FEM). FEM is one of the most used numerical modeling techniques, which can be used for many engineering applications conveniently [3-6]. Figure 3 shows FEM models having an annular protrusion to express the surface roughness. As shown in figures 3(a)-3(d), Modal A has no protrusion to be compared, Model B and Model C have different root radius and Model C and Model D have different heights. The model dimensions are determined by considering real pipe roughness. Figure 4(a) shows the results of Model A. It is seen that the strains are almost the same between the inside and outside surfaces for smooth surfaces. Figure 4(b) shows that even the slight protrusion like Model B causes different strains between the inside and outside surfaces. Figure 4(c) shows that if the root radius becomes a bit smaller like Model C the insider strain becomes larger significantly. Figure 4(d) shows that the higher protrusion height causes larger strain difference between inside and outside surfaces, which may lead the line scar creation at the film inside surface. Figures 4(a)-4(d) shows that the surface roughness affects largely the line scar creation.
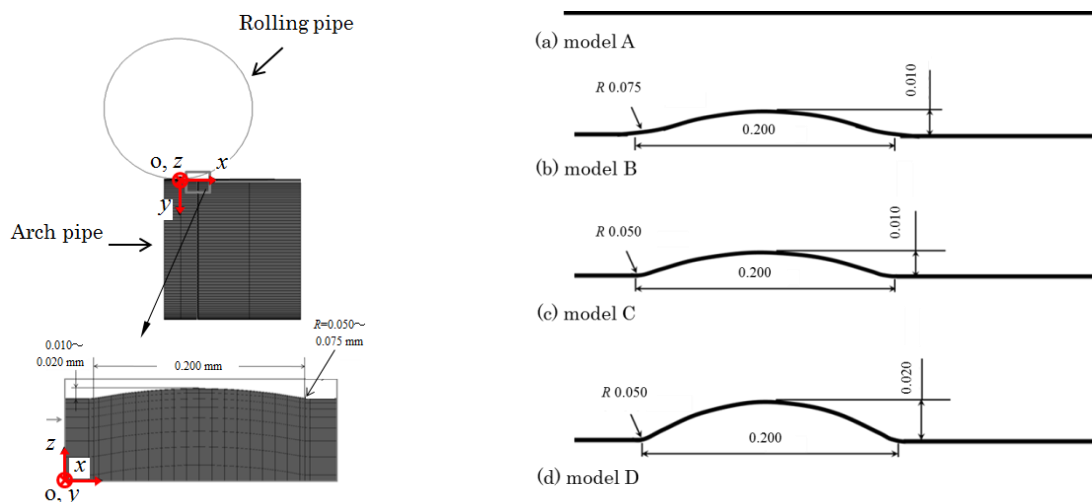

Figure 3. FEM models having an annular protrusion at the arch pipe outer diameter to express the surface roughness.
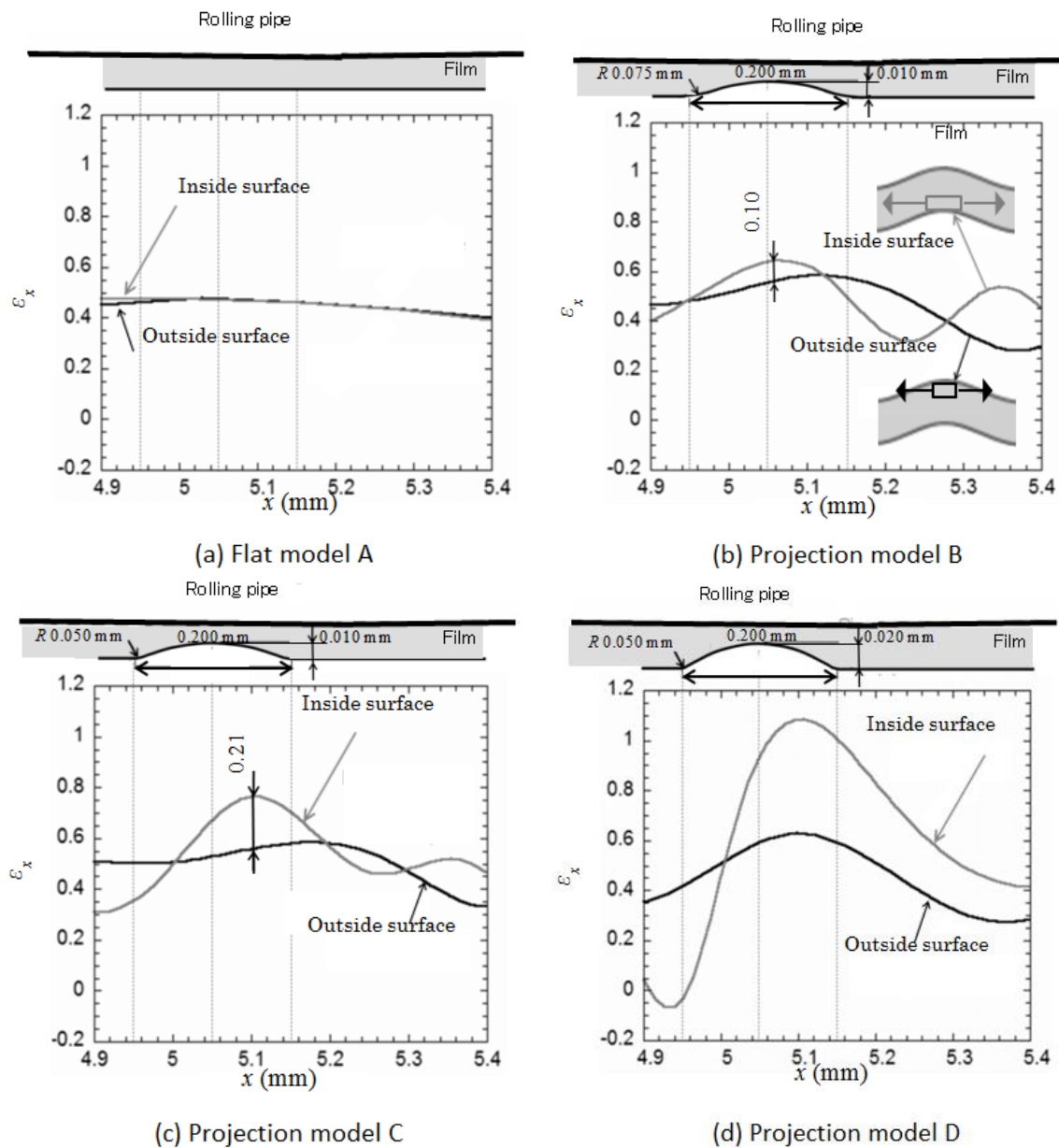
Figure 4. Film elongation along the inside and outside surfaces of the film.

3. Rolling contact analysis and results for coating pipe

As shown in the previous section, the pipe surface roughness leads to the line scar creation. In this section, to prevent the film damage, the pipe coating effect will be discussed. Note that the greenhouse pipe temperature reaches 70 ℃ in summer. The previous study shows that at 70 ℃ the rolling contact stress caused line scars on the plastic film, and therefore, temperature largely affects the damage to plastic films [4]. The pipe coating may be useful for reducing the pipe temperature as well as for reducing the pipe surface roughness. In this study, steel pipes coated with ABS resin whose collars are white, gold, black will be considered with the pipe diameter 38 mm.

   Table 1 compares the numbers of line scar and crease for three kinds of coated pipe under the same temperature T=70 ℃. Compared to no coating, the coated pipes can prevent the line scar and crease creation drastically because of smaller surface roughness. Under the same heating condition, Table 2

compares the numbers of line scar and crease for three kinds of coating pipe. It is seen that when the steel pipe temperature reaches 70 ℃, the coated surface temperature is higher. Although the coated pipes do not prevent rising temperature, they can decrease the number of line scar under the same heating condition. It may be concluded that the white coating is the most effective to prevent the film damage.

Table 1. Number of line scar/cm and number of crease/cm for three kinds of coating pipe under P=75 N, T=70 ℃.

Support pipe	Temperature (℃)	Roughness R_y (μm)	Number of creases per centimeter n_{crease}	Number of line scars per centimeter $n_{linescar}$
Steel pipe ϕ38	70	7.38	many	3.85
Coating pipe ϕ38 (white)	70	1.90	0.75	0
Coating pipe ϕ38 (gold)	70	1.08	1.45	0.55
Coating pipe ϕ38 (black)	70	2.30	0.65	0

Table 2. Number of line scar /cm and number of crease/cm for three kinds of coating pipe under the same heating and P=75 N.

Support pipe	Temperature (℃)	Roughness R_y (μm)	Number of creases per centimeter n_{crease}	Number of line scars per centimeter $n_{linescar}$
Steel pipe ϕ38	70	7.38	many	3.85
Coating pipe ϕ38 (white)	70	1.90	0.75	0
Coating pipe ϕ38 (gold)	80	1.08	many	2.43
Coating pipe ϕ38 (black)	90	2.30	many	2.50

Table 3 indicates the stress and deformation of film type A in [4] obtained by FEM when due to the support pipe is changed. Here, steel pipe, resin pipe and steel pipe coated resin pipe are considered. Assume that the coated resin pipe consists of steel and resin layers, each of which has 1 mm thickness. Note that steel Young's modulus is more than 7 times larger than Young's modulus of resin. It is seen that the maximum thickness reduction of the resin pipe is 20% smaller than the one of the steel pipe. The film deformations are almost the same for the steel pipe and the coated pipe within 3%.

Table 3. Stress and deformation of film type A in [4] due to three kinds of support pipes when T=70 ℃, P=75 N, μ=0.3, and $d_1=d_2$=38 mm.

	Steel pipe	Resin pipe	Coating pipe
Young's modulu's (MPa)	21000	2900	Outside 2900 Inside 21000
Poisson's ratio	0.3	0.35	Outside 0.35 Inside 0.3
Maximum contact pressure (MPa)	6.81	4.70	7.43

Contact area (mm^2)	10.18	11.56	11.31
Maximum thickness reduction	0.120	0.096	0.117

4. Rolling contact experiment and results for perforated film

Perforated films are often used as a plastic film tunnel which covering whole crops and as a mulch material placed on the soil surface to maintain moisture, reduce weed growth, mitigate soil erosion and improve soil conditions [7,8]. Although perforated films are not often used for traditional greenhouses, they are planed to be used for automated ventilation system to control summer temperatures adequately. However, perforated films look susceptible to the rolling contact damage. In this paper rolling contact machine in figure 1 will be used to investigate the hole effect on the rolling contact damage.

Here 3 mm diameter holes spacing 16.5 mm on the film type D will be considered since this diameter is known to provide good ventilation without losing protection against rain. The previous study [4] showed that film type D is the most desirable film for automated ventilation system because line scars handly appeared at temperatures under 70 ℃. The temperature was set to T = 70 ℃, and the same diameter for 38 mm for flame pipe and rolling pipe. The number of cycle N=300. Figure 5 shows two types of rolling paths considered in this study, that is, (a) the path along the hole centres and (b) the path along the hole edges.
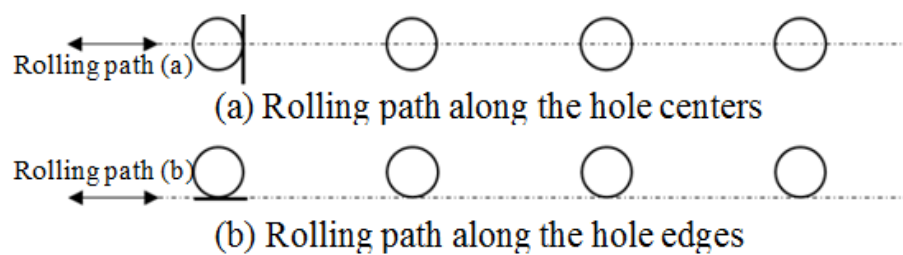

Figure 5. Definition of rolling path (a), (b).

Table 4. Number of line scar/cm of plastic film type D when *P*=75 N, *T*=70 ℃ and $d_1=d_2$=38 mm.

Shape of film	Holes		
Number of line scar	Hole center	Hole edge	Without hole
Number of line scar per centimetre $n_{line\ scar}$	0	5	3
	0	0.25	0.15

Table 4 show the number of line scars/cm for film type D. As shown in table 4, no line scar can be seen after the rolling contact of the path (a) in figure 5 along the hole centres. Figures 6(a) and 6(c) show the film after rolling contact when the path is in figure 5(a). It is seen the film damage due to the rolling path (a) in figure 5 is much smaller compared to the film damage without hole shown in figure 7. As shown in figure 6(c), the circular hole is deformed but no line scar can be seen. The line scar can be formed from the wavy creases after they are folded oved by the rolling contact [4]. In perforated films, the creases disappear when the wavy creases are pushed into the holes by rolling contact. This is why no line scar can be seen in figure 6(c). Perforated films may reduce the damage of the film due to the rolling contact.
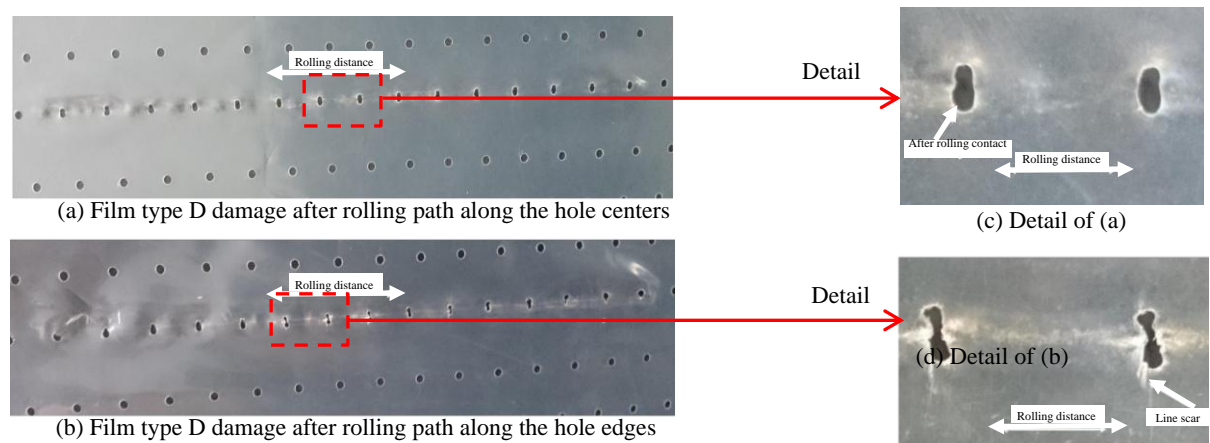
(a) Film type D damage after rolling path along the hole centers

(b) Film type D damage after rolling path along the hole edges

(c) Detail of (a)

(d) Detail of (b)

Figure 6. Perforated films type D in [4].

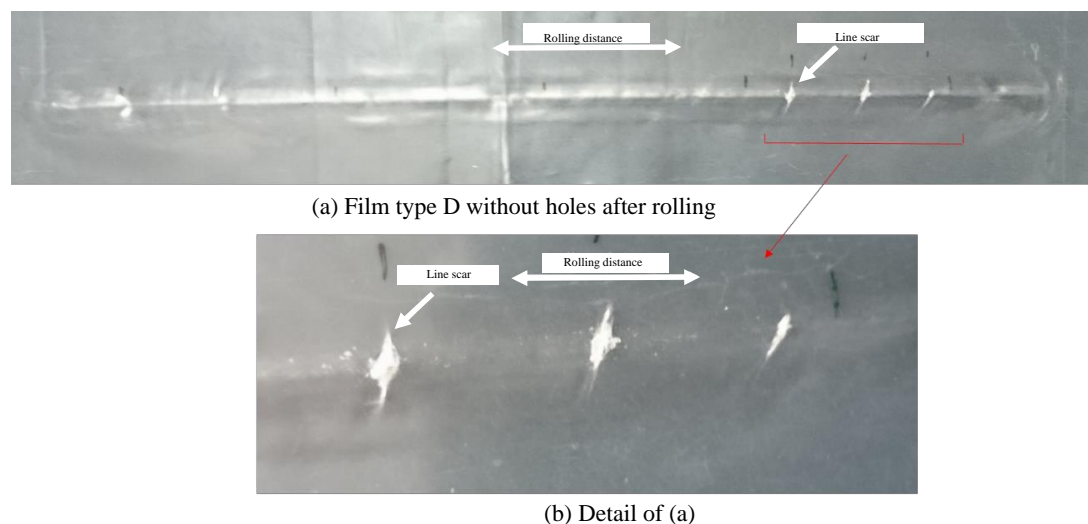(a) Film type D without holes after rolling

(b) Detail of (a)

Figure 7. Film type D line scars without holes.

Figures 6(b) and 6(d) shows the film damage after rolling contact in figure 5(b) whose path is along the hole edges. The stretched zone can be seen in figure 6(b) similar to figure 7. The line scar also can be seen in figure 6(d). This is because many wavy creases are gathered around the hole edges and they are folded over and lead to the line scar as shown in figure 6(d). Larger hole deformation also can be seen in figure 6(d) compared to the deformation in figure 6(c). Generally speaking, the perforated film damage is smaller than or nearly equal to the damage of the film without hole because the holes reduce the average rigidity of the film and therefore contributes to supress the creation of the wavy creases.

5. Conclusions

A novel greenhouse is being used recently since automated rolled-up ventilation system is contained in the roof to control the temperature. Until now, however, full-opening type greenhouse are not widely used because the plastic film deteriorates in three or four months due to the frequent movement of the roll-up system. To prevent the film damage under rolling contact loading, in this paper, rolling contact simulation and experiment were conducted by focusing on the surface roughness of the flame pipe. Then, the conclusions can be summarized

- FEM rolling contact simulation was performed to clarify the surface roughness on the film damage by assuming a single protrusion on the smooth surface. It was found that larger film strain can be seen at the inner film surface compared to at the outer film surface. With

decreasing the root radius of the protrusion and with increasing the height of the protrusion the difference become larger. The larger difference may lead the line scar creation at the film inside surface.

- The experimental study showed that the number of line scar increases with increasing the surface roughness of the pipe. The results can be explained from the FEM simulation considering surface roughness.
- Coated pipe may reduce the film damage. This is because the pipe roughness becomes smaller by the coated layer.
- Perforated film may reduce the damage of the film. This is because the holes reduce the average rigidity of the film and therefore contributes to supress the creation of the wavy creases.

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