Development and Simulation of Extrusion Lamination Process with Polyethylene

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Extrusion lamination is one of the techniques used for laminating different materials, and is widely used as the manufacturing process for packaging films for products such as foods, cosmetics, and pharmaceutical products in order to obtain improved film properties such as gas barrier, heat sealing, and film strength.

Autoclave-type high-pressure low-density polyethylene (PE-HPLD) is generally used in extrusion lamination applications because of its good neck-in property. Recently, however, the packaging industry has desired reductions in the volume of materials and high-speed processing. Therefore, plastic resins with good draw-down properties are needed. Sumitomo Chemical Co., Ltd. has developed a tubular-type PE-HPLD which exhibits a good balance of neck-in and draw-down properties, although neck-in and draw-down properties have a trade-off relation.

In this article we investigated the effects of shapes of deckles, and setting positions of deckles and rods on extrusion processing properties. As a result, we made their relations clear.

Furthermore, we also carried out a viscoelastic simulation of the extrusion lamination process using computer aided engineering developed by Sumitomo Chemical Co., Ltd. The simulation could predict the neck-in phenomenon and thickness distribution for extruded PE-HPLD.

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Introduction

The types of packages and containers in circulation are extremely wide-ranging: glass bottles, aluminum cans, detergent containers, gift-wraps, food packaging films and so forth. According to the statistics for 2007, total expenditure on packages and containers reached 6.2 trillion yen[1]. The theme of this article, extrusion lamination processing, plays an important role in manufacturing paper and plastic products. By laminating polyethylene (PE) onto paper through the extrusion lamination process, water resistant paper products such as milk cartons can be obtained. In addition, by laminating PE onto oriented nylon films (ONy), barrier films or other similar films, various types of plastic products such as food packaging films can be obtained.

Polyethylene (PE)

1. Classification of PE

PE ($-(CH_2-CH_2)_n-$) is produced by polymerizing ethylene ($CH_2=CH_2$). It is either a semitransparent or translucent plastic. Under JIS K6922-1, PE has been classified into three types according to its density (d): high-density PE (PE-HD) ($d \geq 942\text{kg/m}^3$), medium-density PE (PE-MD) ($942 > d \geq 930$) and low-density PE (PE-LD) ($930 > d \geq 910$).

PE-LD can be further classified into two types according to its manufacturing method: (i) PE-LD (PE-HPLD) obtained through a high pressure method in which radical polymerization is conducted under high temperature and high pressure (200–300°C, 100–300MPa) and (ii) linear PE-LD (PE-LLD) obtained by copolymerizing ethylene with an α-olefin using a Ziegler catalyst or a Metallocene catalyst.

Although PE-HPLD has outstanding processability, some properties of the final product, such as mechanical strength, are not satisfactory. Conversely, although PE-LLD possesses excellent mechanical properties, it does not possess good processability.

In recent years, our company has launched Easy Processing Polyethylene (EPPE) products (brand names: SUMIKATHENE®EP and EXCELLEN®GMH®) which possess both the strength of PE-LLD and the easy-to-process characteristics of PE-HPLD.

With regard to the abbreviation codes for plastics, we have conformed to JIS K6899-1: 2006 (e.g.: although LDPE was commonly used for low density polyethylene conventionally, we have used PE-LD as stipulated by JIS.)

2. PE Market

According to the statistics released by the Japan Petrochemical Industry Association[1], PE is the most general-purpose plastic, for which annual domestic shipments reached 2,547,000 tons (fiscal year 2007). Of this total shipment quantity, PE-LD accounts for 1,580,000 tons. The main fields of application of PE-LD are wide ranging, including films, extrusion lamination (laminated paper), injection molding, wire coating, hollow molding and pipes (**Fig. 1**). PE-HPLD is mainly used for purposes that require specific processability, such as neck-in, as required in extrusion lamination processing methods.

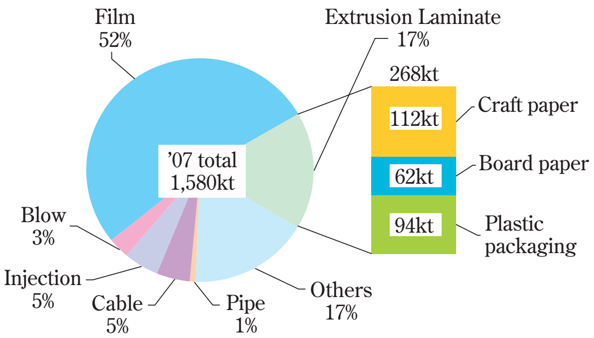

Fig. 1 Shipment according to application (HPLD and LLD) [Data from reference 3)]

3. Manufacturing Process and Molecular Structure of PE-HPLD [4)–10)]

PE-HPLD is produced by conducting radical polymerization under high temperature and high pressure. It can be roughly classified into two types, depending on the shape of the reactor: autoclave (AC) type (also referred to as vessel type) and tubular (TB) type.

AC-type PE-HPLD can be obtained by conducting polymerization in an AC reactor. In this method, the uniformity in the reactor can be maintained by stirring the molten PE. However it is harder to remove the heat of polymerization since the surface area of the reactor is smaller than that of the TB type.

On the other hand, TB-type PE-HPLD can be obtained by conducting polymerization in a tubular reactor having an internal diameter of 25–50mm and a length ranging from a kilometer to several kilometers. The PE polymerized in the tube is then discharged due to the pressure difference between the inlet and outlet ports. Since the surface area of the reactor in the TB type is larger than that of the reactor in the AC type, it is easier to remove the heat of polymerization.

A unique characteristic of the molecular structure of PE-HPLD is its complex long chain branched structure. The degree of long-chain branching (LCB) varies depending on the polymerization conditions. The higher the pressure and/or the lower the temperature become, the lower this degree becomes. In addition, the molecular structure of polymerized PE varies depending on the shape of the reactor. Since polymers, radical initiator and propagating radical ends are stirred vigorously in the AC reactor, the probability of the chain transfer increases. Due to such a reacting condition, polymerized PE of the AC type contains more LCB than polymerized PE of the TB type. **Fig. 2** depicts the typical molecular weight distributions of PE polymerized using each method.

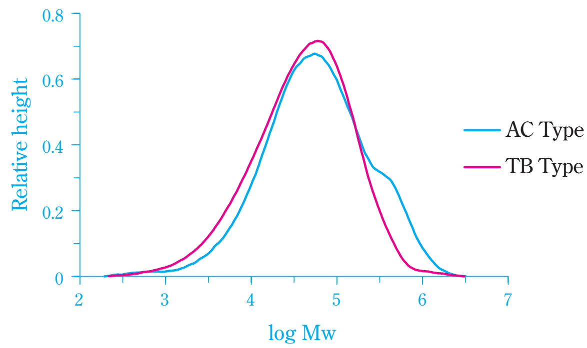

Fig. 2 Molecular weight distribution of PE-LD (AC and TB type)

4. Typical Property of PE-LD

(1) Density (*d*) (Units: kg/m^3)

d is a gauge of the crystallinity index. The larger the *d* value, the higher the crystallinity index becomes, mainly affecting the product's properties. For example, if the *d* value increases, the product's rigidity also increases, thus adding more rigidity to the PE-LD when processing into a film and improving its heat resistance. On the other hand, if the *d* value decreases, the product becomes more flexible and will have higher elasticity and impact resistance.

(2) Melt Flow Rate (*MFR*) (Units: g/10min.)

The *MFR* of PE can be obtained using the following procedure: (1) a sample is poured into a cylinder heated to 190°C, (2) a weight of 21.18N is then placed on a piston, and (3) the weight of the resin extruded from a capillary die is measured for 10 minutes.

The *MFR* is a gauge of molecular weight. The larger the *MFR* value, the smaller the molecular weight, thus affecting the product's processability and properties. For example, if the *MFR* value increases, the product's melt viscosity decreases, which is suitable for high-speed processing. However, since its molecular weight is smaller, the mechanical strength of the film decreases.

(3) Swelling Ratio (*SR*) (Units: none)

The *SR* value can be obtained by dividing the maximum diameter of the strand-like PE extruded from the capillary die when measuring *MFR* by the diameter of the die.

The *SR* is a gauge of melt elasticity (degree of branching). The larger the *SR* value, the larger the elasticity, thus affecting the product's processability and properties. For example, the larger the *SR* value, the smaller the neck-in when manufacturing a flat die cast film, which is desirable for this type of film. However, the film becomes opaque, not transparent.

5. PE Grade for Extrusion Lamination

In the 1960s, when implementation of extrusion lamination for the production of laminates began, the take-up velocity for this method was not very fast (≤80m/min.). Therefore, smaller neck-in was particularly required in PE grades for extrusion lamination.

In order to reduce neck-in, it is more effective to have larger melt elasticity. For this reason, AC-type PE-HPLD is more commonly used than the TB type. This is because AC-type PE-HPLD has more LCB and high molecular weight components, thus increasing the resin's melt elasticity.

In addition, even with the same AC-type PE-HPLD, neck-in can be further reduced by (i) reducing the *MFR* value and (ii) increasing the *SR* value.

In later years, extrusion laminators having higher take-up velocities were developed. Accordingly, the demand for resins able to undergo higher take-up velocities gradually increased. Therefore, we have been developing PE grades that can particularly accommodate higher take-up velocities by adjusting the molecular structure.

Furthermore, due to higher raw material costs, down gauging and higher productivity have become increasingly required. In order to achieve down gauging and higher productivity (higher take-up velocities), it is necessary to use resins that have outstanding draw-down properties. Therefore, our company has further improved conventional TB-type PE-LD, which already has better draw-down properties than the AC type, and achieved a grade particularly which is suitable for extrusion lamination processing. However, when draw-down properties improve, neck-in becomes larger. Therefore, it is necessary to reduce edge beads in the processing conditions.

In the next chapter, we will briefly explain extrusion lamination processing. We will then summarize the effects of changes to the processing conditions in terms of neck-in and edge beads, using several types of PE.

Extrusion Lamination

1. Definition of Lamination

The term "lamination" means overlaying a number of layers of plastic films, paper or aluminum foils (Al). By laminating different types of materials, the favorable characteristics of each material can be utilized, and the shortcomings of each material can be made up for.

Using a packaging material for green tea (structure: laminated with paper/Al/ONy/PE sealant) as an example, it can be seen that each material has the following features:

- Paper: Although it is attractive, it has no barrier properties and does not have sufficient mechanical strength.
- Al: Although it has an excellent moisture and gas barrier properties, it can become easily wrinkled and ripped off.
- ONy: It has excellent mechanical strength.
- PE Sealant: It adds heat sealing properties.

By laminating these materials, it is possible to obtain a packaging material that has an attractive appearance, moisture barrier properties, excellent mechanical properties and heat sealing properties.

Although there are several lamination techniques, the most typical ones are extrusion lamination and dry lamination. Other techniques include wet lamination, thermal lamination and hot-melt lamination.

In extrusion lamination processing, the molten resin is extruded in film shape then adhered onto a substrate (**Fig. 3**). If the molten resin is made of PE, the processing temperature should be set to approximately 300–330°C. Adhesion with the substrate occurs when the PE becomes oxidized due to exposure to the air while being extruded from the flat die and laminated onto the substrate (air gap). When using a plastic film such as poly (ethylene terephthalate) (PET) and ONy as the substrate, an anchor coating (AC) agent is applied in order to increase the adhesive strength between the PE and the substrate. Also, when using paper as the substrate, the AC agent is not applied because the adhesive strength increases when the molten PE gets into the paper fiber (anchoring effect).

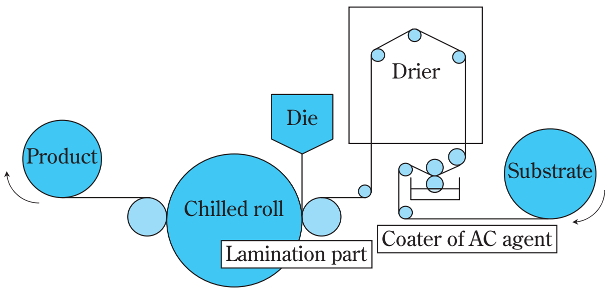

Fig. 3 Diagram of Extrusion lamination

In dry lamination, on the other hand, an adhesive is applied onto one of the materials and then adhered to the other material after evaporating the solvent contained in the adhesive.

2. Required Properties in Extrusion Lamination Processing [11]

(1) Neck-in

Neck-in is a phenomenon by which the width of molten PE extruded from the flat die becomes smaller than the width of the die exit. The neck-in length can vary depending on the level of elasticity of the molten PE. Moreover, the PE at both edges of the film becomes thicker than that in the central area, as the width of the PE becomes smaller at the die exit. These particular areas are called edge beads. The larger the neck-in value, the larger the edge beads (**Fig. 4**).

It is desirable to have a smaller neck-in value because films with smaller neck-in value have a wider field of application, thus decreasing loss. Neck-in can be decreased by taking the following measures: (i) selecting the resin, (ii) decreasing the processing temperature, (iii) increasing the take-up velocity and (iv) decreasing the air gap (the distance between the bottom end of the die and the laminating part). Edge beads can be removed by trimming or the height of the edge beads can be flattened. It is not desirable to trim edge beads to a great extent, as this is wastage. Edge beads can be removed by flattening the resin at both edges by adjusting the rod position or the shape and position of the deckle set inside the die (described later).

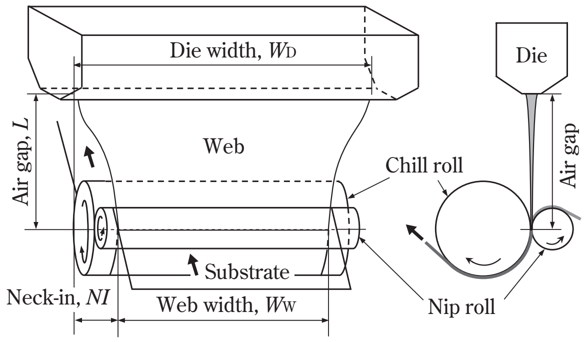

Fig. 4 Diagram of flat die laminate process

(2) Draw-down Properties

In extrusion lamination processing, when using a plastic substrate, it is necessary to coat the substrate with an AC agent. Since this coating process is rate-limiting, the maximum take-up velocity is approximately 200m/min. When using a paper substrate, however, the take-up velocity occasionally exceeds 500m/min. as application of the AC agent is not required.

Draw-down properties can be evaluated by the maximum take-up velocity in terms of processability. As the processing speed is gradually accelerated, it will reach a point where the end of the molten PE becomes severed, thus making processing impossible. Draw-down properties can be improved by (i) selecting the resin and (ii) increasing the processing temperature. Also, by improving draw-down properties, thinner molten resins can be attained. Furthermore, there is a trade-off relation between neck-in and draw-down properties.

(3) Other Information

Other required properties include lamination strength, heat sealing properties/hot tack properties, low odor/taste properties, mechanical properties and resin exchange suitability.

3. Recent Efforts

Due to cost-cutting requirements, improving productivity through down gauging (thinner films) and high-speed processing is desired.

Processing machine manufacturers have been striving to improve film thickness and processing stability when increasing take-up velocities.

Our company has also been developing resins that enable down gauging and high-speed processing. We are also examining processing conditions under which our customers can appropriately use such new resins.

In the next chapter, the effects of changes to processing conditions will be described using several actual examples.

Effects of Processing Conditions on Extrusion Lamination Processability

1. Extrusion Laminator for Testing

Sumitomo Heavy Industry Modern's coextrusion laminator (screw diameter: ϕ65mm×2) was used for the evaluation of extrusion lamination processability. This flat die is equipped with 2 inner deckles at each end, and rods are situated on the downstream side (**Fig. 5**). The greatest uniqueness of this type of flat die is that it has a broader adjustment range for the thickness of the edge of the extruded resin than that of other types (triangle rod type, full-width embedded deckle type), since the deckles are set on two levels[12].

2. Processing Conditions

AC-type PE-HPLD for extrusion lamination (AC-1) and TB-type PE-HPLD (TB-1) were used for comparison.

As shown in **Fig. 6** (a), the test was conducted under the following conditions: x, the range of distance between the die's upper deckle and lower deckle, is 0–50mm, and y, the range of distance between the lower deckle and the rod, is 0–60mm.

Furthermore, the effects of deckle shape were also examined using three types of deckles having different tip shapes (R=20, R=90-10, R=130-5) (**Fig. 6** (b)).

3. Effects of Resin Types (Fig. 7)

The AC-type PE-HPLD had a smaller neck-in value than the TB-type PE-HPLD. Also, the heights of the edge beads were lower and the widths were narrower. On the other hand, because the TB-type PE-HPLD

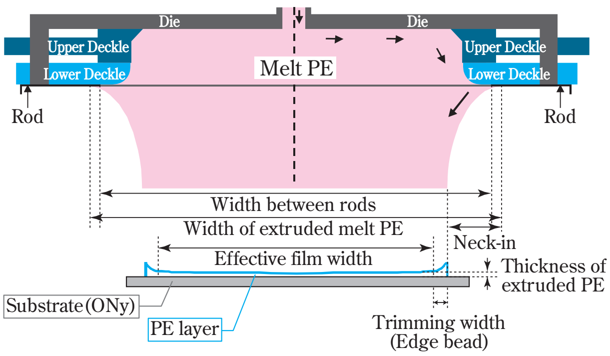

Fig. 5 Schematic diagram of flat die used in this article

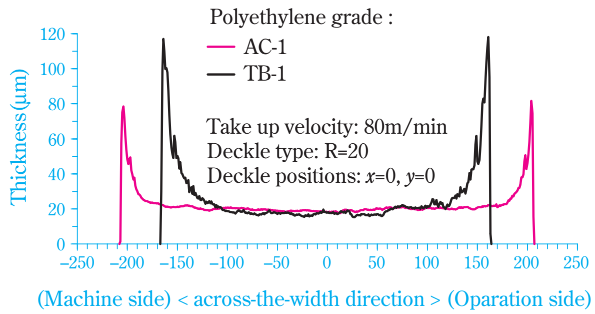

Fig. 7 Thickness distribution of extruded AC-type and TB-type PE-HPLD resins

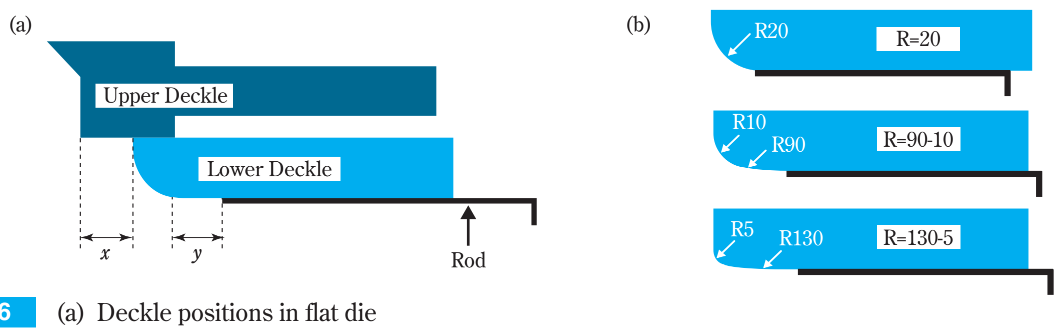

Fig. 6 (a) Deckle positions in flat die
(b) Schematic illustration of deckles

had a larger neck-in value, the resin concentrated towards the edges, thus making the edge beads higher and wider. As a result, the width of the effective film became narrower. It can be concluded that these differences were due to differences in the molecular structures of the resins, which was due to differences in the resin manufacturing methods.

4. Effects of Deckle Positions (Fig. 8)

The greater the *y* value shown in **Fig. 6** (a), which was set by maintaining the interval between the rods ("Width between rods" described in **Fig. 5**) and pushing the deckle towards the inside, the lower and narrower the edge beads. If the deckle is pushed inward beyond a certain depth (50mm in this case), the outside film is pulled excessively, thus making the film extremely thin. Therefore, it can be concluded that the optimum condition in **Fig. 8** is $y = 30$mm.

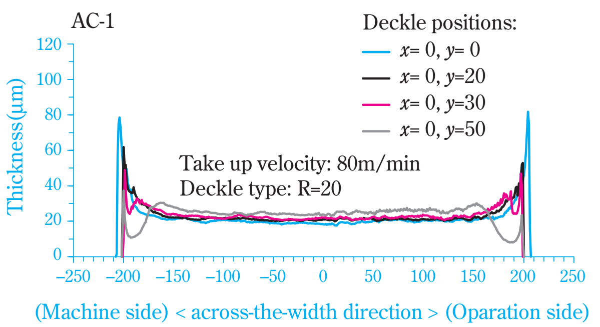

Fig. 8 Effects of deckle positions (*x*, *y*) on thickness distribution of extruded AC-type PE-HPLD

5. Effect of Deckle Shape (Fig. 9)

The web shape of the molten resin varies depending on the deckle shape. Deckles having a shape whereby R is nearer the outside in the width direction exhibit a smaller neck-in value, lower edge beads and narrower edge bead widths than other deckle types. When processing an AC-1 resin at a temperature of 320°C and a take-up velocity of 80m/min., the optimum deckle shape was R130-5.

By using the optimum deckle shape under the optimum processing conditions (the appropriate take-up velocity and resin temperature), a completely flat surface can be obtained in the final product.

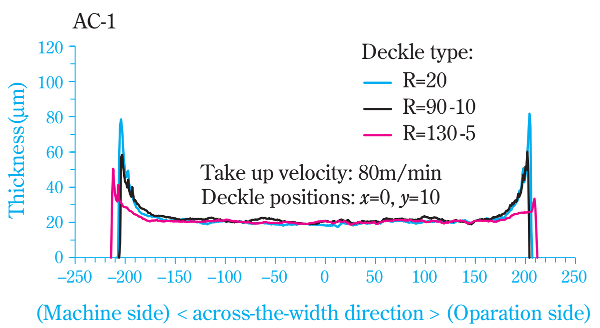

Fig. 9 Effects of deckle types on thickness distribution of extruded AC-type PE-HPLD

6. Development of TB Type PE for Extrusion Lamination

(1) Development Process

It is considered that TB-type PE-HPLD is more suitable than conventional AC-type PE-LDPE to meet today's market needs, which are down gauging and higher productivity. For this reason, we have developed a TB-type PE-HPLD grade which is particularly suitable for extrusion lamination (TB-New). In this grade, while the draw-down properties of the conventional grades are maintained, neck-in has been reduced. Retaining the conventional draw-down properties enables down gauging and high-speed processability.

(2) Improved Neck-in Effects (**Table 1**)

It is obvious that the TB-New grade has significantly improved neck-in properties compared to conventional TB-type PE-HPLD (TB-1). However, compared to AC-type PE-HPLD (AC-1), it has a slightly larger neck-in value. The neck-in value can be decreased by reducing the air gap as shown in **Table 1**. Since the air gap of a commonly used monolayer die is approximately 100mm, it is thought that this level is not a particular problem. In the next chapter, we will demonstrate the improved neck-in effects by simulating extrusion lamination processing using CAE (Computer Aided Engineering) technology.

Table 1 Extrusion processing properties of PE-HPLD

Type	Grade	Air gap(*) (mm)	Neck-in(*) (mm)	Draw down (m/min)
AC	AC-1	160	35	300
TB	TB-New	160	45	> 400
		190	56	> 400
		220	68	> 400
	TB-1	160	63	> 400

(*) Take up velocity: 190m/min

(3) Down Gauging and High-speed Processability

In the investigation into down gauging, it has been known that the phenomenon of edge oscillation (vibrations occurring at the edge of the molten web extruded from the flat die) and the phenomenon of edge breaking (breaking of the edge of the molten web extruded from the flat die) can cause problems[13]. With edge oscillation, the position of the molten web edge changes irregularly during the processing. The oscillation phenomenon can be evaluated by the degree of these changes. The greater the degree, the more unstable the processing. Therefore, down gauging must be examined under conditions in which the processing does not become affected by these phenomena. **Table 2** shows the results of effects of the edge oscillation and edge breaking phenomena when laminating TB-New using extrusion lamination with an average resin thickness of 3.3μm. Changing deckle positions greatly affects these phenomena. Therefore, these problems can be solved by optimizing the deckle positions. Furthermore, **Fig. 10** shows the effects of edge beads. This is an example of the measurement of the thickness distribution of an extruded TB-New having an average thickness of 3.3μm. From this figure, it is clear that by optimizing the deckle positions, edge beads can be also adjusted to a level that does not affect processing.

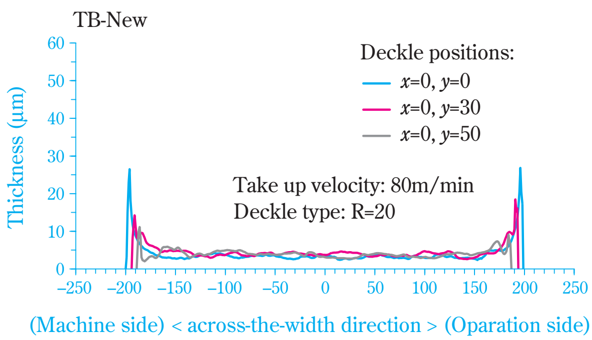

Fig. 10 Effects of deckle position (x, y) on thickness distribution of extruded TB-New

On the other hand, because there is virtually no problem in terms of high-speed processability, TB-New can be processed at a velocity of more than 400m/min, as shown in **Table 1**.

Processing Simulation

1. Trends in Simulation Technology

In extrusion lamination processing and cast film processing, heat and flow in the air gap affect the processability and product properties in addition to heat and flow inside the processing machine. Many experiments and simulations have been conducted thus far in order to investigate flow conditions in the air gap. In this chapter, a number of typical studies will be introduced.

Since the thickness of the web in the air gap is sufficiently small compared to its width to be ignored, pseudo-three-dimensional calculations, in which physical quantities are averaged toward the thickness direction, have been conducted thus far[14)–17)]. Using a Newtonian fluid, Sakaki *et al.*[18)] conducted three-dimensional calculations for the first time. It was confirmed that the calculation results were quite consistent with experimental values from cast film processing using high density polyethylene. Subsequently, Satoh *et al.*[19)] conducted conventional pseudo-three-dimensional calculations, and confirmed that the results were quite consistent with those of the three-dimensional calculations.

In this chapter, simulations using our proprietary PE-HPLD for extrusion lamination processing will be reported. The simulation results were compared with experimental values for the purpose of investigation into the effects of resin types and processing conditions on neck-in and edge beads. In addition, the mechanisms by which neck-in occurs were also investigated.

Table 2 Effects of deckle positions (x, y) on edge oscillation and edge breaking of TB-New

		Deckle positions							
x	mm	0	0	0	30	30	30	50	50
y	mm	0	30	50	0	30	50	30	50
Edge oscillation	mm	3	4	25	10	7	27	41	38
Edge breaking(*)	(—)	N	N	N	N	N	N	Y	Y

(*) Y: edge break, N: not edge break

2. Simulation of Extrusion Lamination Processing

(1) Simulation Method

A non-isothermal viscoelastic flow simulation was conducted using "Polyflow" (ANSYS Inc.), software based on the finite element method. The exponential viscoelastic fluid model Phan-Thien/Tanner [20] was used for the fluid model. Also, the Arrhenius law was adopted for the temperature dependence of the viscoelasticity. AC-1, TB-New, TB-1 were used as the materials. **Fig. 11** shows the viscoelasticity of TB-New at 130°C.

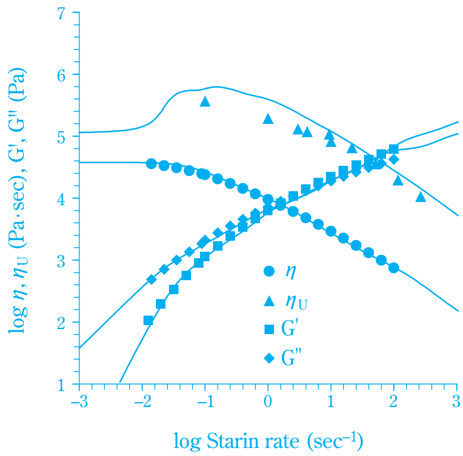

Fig. 11 Viscoelasticity of TB-New at 130°C

(2) Verification of Simulation

The web shapes obtained from the simulation were compared with experimental values. **Fig. 12** (a) shows the web shapes at a take up velocity of 120m/min and an air gap of 160mm. The web shapes in the experiment were measured using observational photographs. Half the lower side of the web could not be observed, as it was hidden by the nip roll. The width of the web at the lower edge was measured using the product coating width. The simulated web shape was almost consistent with the experimental values for all of the materials. **Fig. 12** (b) shows the web shapes for different air gaps when using TB-New. In this experiment also, the simulation values and experimental values were quite consistent. Thus, the validity of the simulation was confirmed quantitatively.

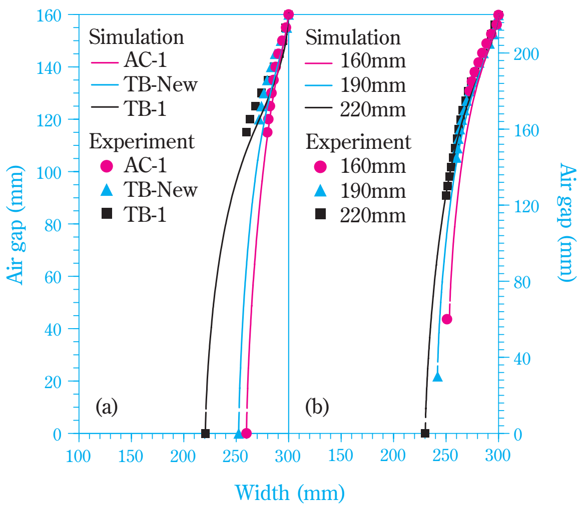

Fig. 12 (a) Comparison of the web shapes at different materials
(b) Web shapes for TB-New at different take up velocity

(3) Effects of Resins and Processing Conditions

The effects of resins and processing conditions on neck-in and edge beads were investigated. **Fig. 13** shows the relationship between neck-in and the take up velocity of each resin. Within the scope of the investigation, AC-1 had the smallest neck-in and TB-1 had the largest of all the resins. Because the *MFR* of AC-1 was the highest, it was clear that *MFR* was not an essential factor for neck-in. It can be also recognized that resins having a small neck-in have lower take-up velocity dependence, thus the range of take up velocity for which neck-in is equivalent is wide.

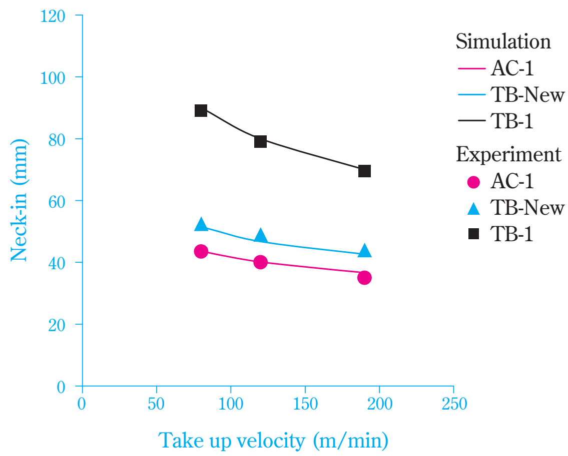

Fig. 13 Relationship between neck-in and take up velocity

Fig. 14 shows the relationship between neck-in and air gap at a take up velocity of 120m/min. As a result of this experiment, the neck-in of each material increased linearly with an increasing air gap. It can be predicted that when the air gap is 0mm, the neck-in will also be 0mm.

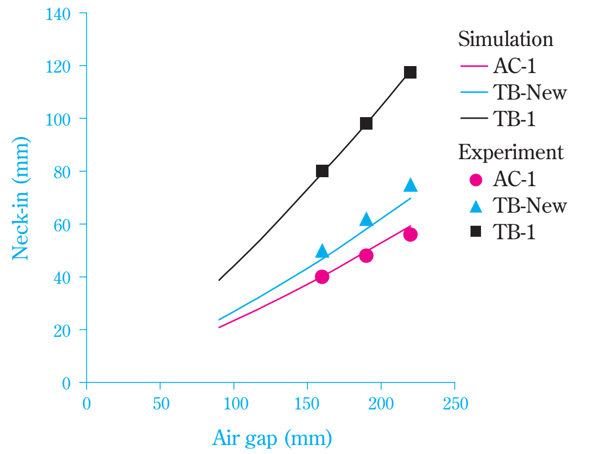

Fig. 14 Relationship between neck-in and air gap

We conducted a simulation of a technique for reducing the edge beads by optimizing the deckle positions, as introduced in the previous chapter. At first, the simulation was conducted on the three-dimensional flow inside a die in which the deckle positions are changed. Next, the velocity distribution at the die exit was used as the boundary condition for the web inlet. **Fig. 15** shows the coating thickness distribution for the reference condition and the various deckle position conditions. By narrowing the deckle intervals, neck-in was increased and the edge beads were decreased. By enlarging the rod intervals under conditions whereby $x=50$ and $y=50$, the edge beads could be reduced without changing the coating width.

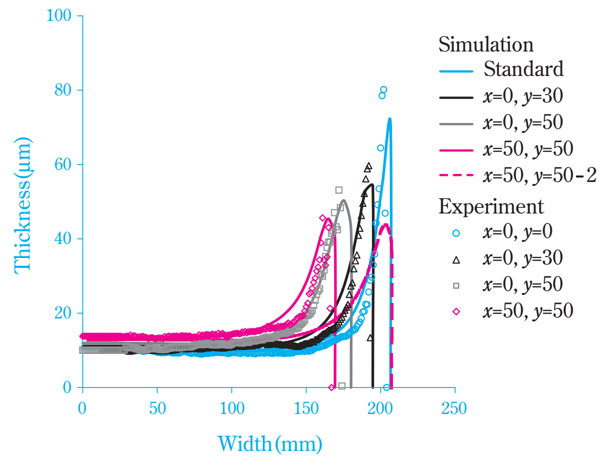

Fig. 15 Thickness distribution at various deckle positions

(4) Mechanisms of the Neck-in Phenomenon

In order to clarify the mechanisms of the neck-in phenomenon, the flow conditions in the air gap were studied. Firstly, the web deformation pattern was examined. **Fig. 16** shows the streamline of the web. Since the streamline is parallel at the central part of the web, it can be understood that only the thickness decreases while the width remains constant. On the other hand, the streamline intervals at the edge part became narrower toward the roll. As a result of examining the relationship between final thickness of the web and the draw ratio, it has been clarified that the center part undergoes planar elongational deformation while the edge part undergoes uniaxial elongational deformation. Numerous reports that support these findings have been published [21)–24)]. Next, the force balance of the web was studied. It has been clarified that the force acting in the width direction is balanced. Canning *et al.*[22)] also confirmed that, in their experiments, the tension of the web was balanced in the width direction.

Fig. 16 shows the neck-in model based on the deformation pattern and force balance of the web [25)–27)]. The balance of the force that affects the small volume element at the web edge will be examined in this section. Eq. 1 can be obtained from the balance of the force in the width direction.

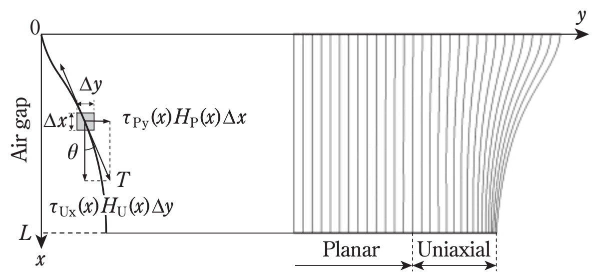

Fig. 16 Streamline of the web for TB-New at 120m/min, L=160mm (right side) and the neck-in model (left side)

$$T\sin[\theta(x)] = \tau_{Py}(x)H_P(x)\Delta x \qquad \text{(Eq. 1)}$$

Where, F represents the tension along web edge, θ represents the angle between the web and x-axis. Eq. 2 can be derived from the assumption that the x-axis component of the tension is balanced with uniaxial elongational force in the x-direction.

$$T\cos[\theta(x)] = \tau_{Ux}(x)H_U(x)\Delta y \qquad \text{(Eq. 2)}$$

Here, τ_{Py} represents the planar elongational stress at the central part in the width direction, H_P represents the thickness of the central part, τ_{Ux} represents the uniaxial elongational stress at the edge in the take-up direction and H_U represents the thickness of the edge. By combinating Eq. 1 and Eq. 2 and then integrating them, the web shape $y\,(x)$ can be obtained.

$$y(x) = \left[\int_0^L dx' \int_{x'}^L \frac{\tau_{Py}(x'')H_P(x'')}{\tau_{Ux}(x'')H_U(x'')}\, dx'' \right]^{1/2} \qquad \text{(Eq. 3)}$$

However, since the web stress and thickness change non-linearly, it is difficult to obtain the analytical solution for Eq. 3. Therefore, we have obtained the web shape $y\,(x)$ by substitution of the stress and thickness of the center and the edge boundaries obtained from the simulation into Eq. 3 and numerical integration. As shown in **Fig. 17**, the estimated values of the neck-in model were quite consistent with the simulation values. This means that they were also consistent with the experimental values, thus confirming their validity.

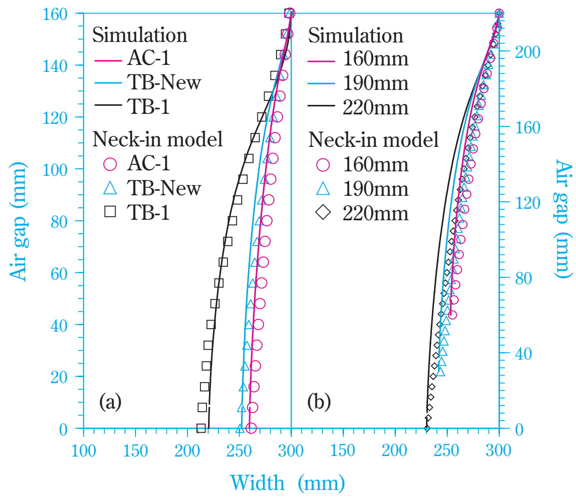

Fig. 17 (a) Comparison of the web shapes at various material
(b) Web shapes for TB-New at different air gap

Considering the thickness and strain rate of the edge and the central part of the web, it can be concluded from Eq. 3 that the neck-in depends on the ratio between the uniaxial elongational viscosity η_U and the planar elongational viscosity η_P. **Fig. 18** shows the relationship between the neck-in of each PE-HPLD and $\langle\eta_P/\eta_U\rangle$. $\langle\eta_P/\eta_U\rangle$ is the mean value obtained within the range from 10^{-3} sec^{-1} to the maximum strain rate for each processing condition. It has been

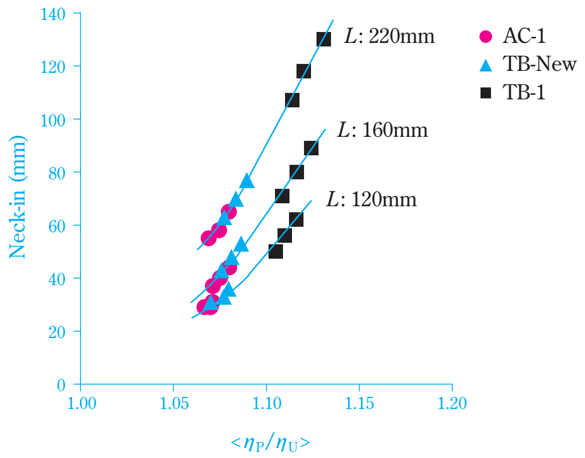

Fig. 18 Relationship between neck-in and viscosity ratio $\langle\eta_P/\eta_U\rangle$

clarified that the neck-in depends on the ratio between the planar elongational viscosity and the uniaxial elongational viscosity, as well as the air gap.

Conclusion

- We have developed a new TB-type PE-LD grade which is suitable for high-speed processability and down gauging.
- We have discovered that edge beads can be reduced by optimizing the processing conditions.
- We have confirmed that the predictions of the CAE technology and the neck-in model were quite consistent with experimental results.

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