Embossing of Polyester Film Laminated Steel

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1. Introduction

Polyester film laminated steel for construction material use has been slightly but steadily replacing polyvinyl chloride coated steel from environmental concern. The conventional method of embossing polyvinyl chloride film or polyvinyl chloride coated steel is to apply the cool emboss roll after softening or melting the film. Few research had been done to clarify the effect of temperature, stress and deformation on embossing thermoplastic polymer like polyethylene film by experimental research and numerical analysis presented by Haber and Kamal.

Different from polyvinyl chloride coated steel, the crystalline polymer like polyester is sensitive to the heat because the crystallization of polyester will lead to the degradation of polyester film. Therefore, non-heated polyester film laminated steel has been tried to emboss the film surface with heated emboss roll in our laboratory instead of embossing the heated steel with the cool roll.

Furthermore, the numerical analysis regarding cross-sectional variation of maximum temperature was conducted and simultaneously softening temperatures of polyester films were measured by thermomechanical analysis (TMA).

It is concluded that the transcription ratio of embossed pattern in the process can be estimated by the numerical analysis with the maximum temperature distribution and the softening temperature.

2. Experiment and Numerical Analysis

2.1. Polyester Film and TMA Measurement

Two kinds of crystalline polyester films were selected in this investigation. One was a non-oriented polyethylene terephthalate (PET) film with a thickness of 75 μm having a melting point of 248°C. The other was a non-oriented copolymer film of polyethylene terephthalate and isophthalate (PET/I) with a thickness of 100 μm having a melting point of 223°C.

Softening temperature of these polyester films were measured by TMA. Thermomechanical analysis was applied to measure polyester films properties using penetration probe, made of quartz glass with point angle of 60° and curvature radius of less than 0.2 mm, at the scanning rate of 10°C/min under the load of 10 g. Here, softening of polyester film was evaluated by the value of penetration depth \( d_P / \delta_t \), that was defined by dividing penetration depth \( d_P \) by film thickness \( \delta_t \) and softening temperature \( T_m \) was defined as shoulder of the softening curve.

2.2. Embossing Process

Figure 1 shows experimental procedure of embossing. A base steel of 0.5 mm thickness was coated to have 30 g/m² of zinc and 40 mg/m² of chromium on each side in advance. Polyester film with 5 g/m² of polyester adhesive was laminated on one side of the electrolytic zinc-coated steel by heating at a temperature of 210°C with the cool nip-rolls of 25°C, and the laminated steel was immediately quenched into water of 30°C.

The above laminated steel was embossed with the emboss roll at 140 to 200°C, with the embossing speed of 40 m/min and the roll-pressing load of 1 800 N. The embossed sheet was immediately quenched into water of 30°C. The embossing roll with outer diameter of \( \phi \) 250 mm and roll-face width of 150 mm was engraved by the sand-blasting pattern with maximum roughness \( R_{\text{max}} \) of 61.3 μm and center line average roughness \( R_s \) of 8.1 μm.

The embossing formability of polyester film laminated steel with various temperatures were evaluated by measuring the surface roughness \( R_{\text{max}} \) and \( R_s \) of polyester film after embossing.

2.3. Numerical Analysis

The embossing formability of polyester film laminated steel is largely influenced by the softening temperature under a constant condition of roll-pressing load. Therefore, in order to estimate the embossing formability, the energy equation of finite-difference form was applied to obtain the variation of the cross-sectional temperature distribution of polyester film laminated steel in embossing process. In case of embossing process by the hot emboss roll, the laminated steel is heated by heat conduction through the surface of polyester film in the emboss roll nip, and quickly cooled into water after embossing as shown in Fig. 1.

Thus, in order to make the temperature distribution obvious in such embossing process, the problem was simplified by the unsteady one-dimensional heat conduction model as shown in Fig. 2. Here, the position \( L \) in steel-feeding direction as a function of time \( \tau \) was decided by \( L = V \tau / 60 \).
Table 1 shows principal physical properties and Table 2 shows conditions of numerical analysis.

The following assumptions are applied:
1) the physical properties are constant;
2) polyester film, steel, emboss roll, and backup roll are never transformed, and thermal contact resistances of them are negligible;
3) emboss roll and backup roll are at the uniform temperature in thickness direction as the initial conditions, and inner walls of these rolls are at the constant and uniform temperature.

The energy equation is
$$\frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial X^2}$$
where $\alpha$ is the thermal diffusivity, $\alpha = k/(c_p \rho)$.

3. Result and Discussion

Figure 3 shows TMA patterns of PET and PET/I films by penetration method. PET and PET/I begin to soften as temperature rises above the glass-transition temperature, and finish to soften at the quite lower temperature than melting point as shown in Fig. 3. The maximum temperature distributions of polyester film in the embossing process are given by means of the numerical analysis in Sec. 2.3.

Figure 4 shows cross-sectional variation of maximum temperature $T_{\text{f,max}}$ of polyester film in the emboss roll nip, where $X_f$ is the distance from surface of film.

The estimation of the embossing formability was conducted from the result of numerical $T_{\text{f,max}}$ in the embossing process. In order to simply estimate the embossing formability with the numerical results, the forming temperature of embossed pattern was defined as softening temperature $T_{\text{ss}}$ of polyester film as shown in Fig. 3. Thus, $T_{\text{ss}}$ was defined as the shoulder of softening curve by means of penetration method, and $T_{\text{ss}}$ of PET film was determined as $105^\circ\text{C}$ and $T_{\text{ss}}$ of PET/I film was determined as $107^\circ\text{C}$.

The estimated $R_{\text{max}}$ could be determined by the thickness where the maximum temperature in roll-nip exceeds the broken line $T_{\text{ss}}$ in Fig. 4. Although the center line average roughness $R_a$ has been usually applied to estimate the embossing formability, the maximum roughness $R_{\text{max}}$ is expected more appropriate to estimate it from the temperature.
distribution and the softening temperature. Figure 5 shows relation between \( R_a \) and \( R_{\text{max}} \). This figure reveals that \( R_a \) of embossed surface of polyester film relates to \( R_{\text{max}} \) and \( R_{\text{max}} \) is possible to estimate the embossing formability. Figure 6 shows a good coincidence between numerical \( R_{\text{max}} \) and experimental one, and the estimation was proved to be appropriate and reasonable. This excellent agreement is caused by the embossing process to heat from the surface of polyester film. This embossing process is similar to TMA penetration method, where the probe penetrates to polyester film in heating.

4. Conclusion

It was found possible to emboss the polyester film laminated steel by the hot emboss roll. The numerical analysis was applied to characterize the maximum temperature distribution in embossing process, and softening temperatures of polyester films were measured by thermomechanical analysis.

Furthermore, the estimation of embossing formability by the numerical analysis together with the softening temperature measurement was found possible with the accuracy of \( \pm 10\% \).

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