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Formability of coated vinyl on sheet metal during deep drawing process

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ABSTRACT

In this study, the formability of vinyl coated metal (VCM) which is sheet metal coated with PET and PVC was studied. VCM has excellent appearances because of the artificial pattern named hairline and is used in home appliances such as washing machines and refrigerators. However, there are problems in the formability of VCM because PET film fracture or delamination occurs when VCM is formed (in particular, in drawing processes) in some cases. To predict the formability of VCM, a finite element numerical model that expressed material damage was established using GTN (Gurson–Tvergaard–Needleman) damage model. Individual materials that would constitute VCM were determined through tensile test based reverse engineering. The numerical model was verified using the results of VCM tensile tests and rectangular deep drawing tests and a good congruence between the results obtained from the numerical model and actual phenomena was identified. In addition, the mechanism for PET films to reach fracture early compared to their elongation in VCM forming was identified. Furthermore, bending processes were simulated using the verified numerical model to examine damage behaviors of VCM according to process variables and Nakazima test was simulated to draw forming limit curves and evaluate the formability of VCM.

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1. Introduction

Vinyl Coated Metal (VCM) is laminated sheet metal mainly used in home appliances. VCM consists of PET, PVC, a adhesive layer, and steel. VCM has good-looking appearances but has problems such as PET film cracks and delamination occurring in forming processes such as deep drawing, bending, and notching. These problems occur in PET only not in PVC.

Kim and Thomson (1990) expressed the behavior of laminated sheets or adhesives inside the sheets separately for a viscoelastic zone having low strain rates and a plastic zone that shows viscous flow behavior. However, they considered about only those laminated steel sheets to which polymer films such as PET and PVC films were not bonded. Takuda et al. (1996) predicted defects occurring during a deep drawing process in laminated steel sheets made by combining mild steel sheets with diverse kinds of aluminum alloy sheets using the damage model proposed by Oyane et al. (1980) and rigid-plastic finite element analysis simulations. However, the said model was not a model that affected materials' yield function. Van den Bosch et al. (2008) studied the characteristics of delamination of metal sheets coated with polymers. Based on the results of this study, Van den Bosch et al. (2009) studied the delamination phenomenon occurring during a deep drawing process. They used von Mises flow stress based elastic–plastic models as numerical models for metal and polymers and expressed adhesive layers using a cohesive zone model. Gurson (1977) suggested the yield function of porous material considering the effect of hydrostatic stress. Tvergaard (1982) supplemented the void nucleation with the normal distribution model by introducing 3 additional factors. Tvergaard and Needleman (1984) added a total volume fraction of void nucleation with a consideration for the drastic decrease of stress under the void coalescence. In conclusion, the GTN model expresses a phenomenon about the occurrence, the growth and the coalescence of the microvoids.

In this study, the material behaviors of polymer films and steels were expressed with GTN damage model and von Mises plasticity. Note that polymers have amorphous and porous structure which means void volume fraction is more affected not by the void nucleation but by the void growth. Material constants and GTN constants were defined using the results of material property tests conducted

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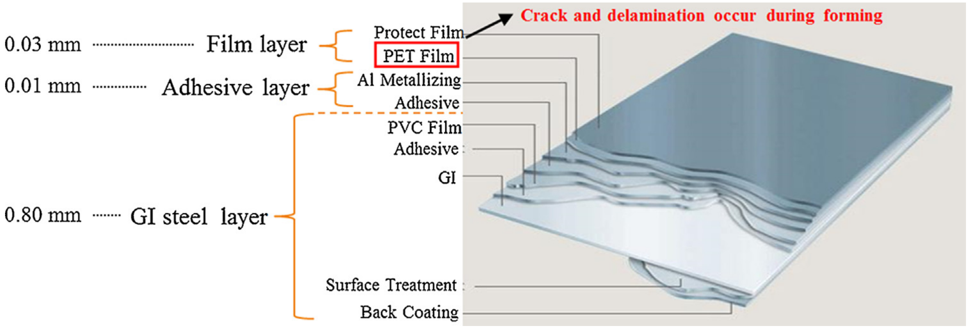

Fig. 1. Composition of VCM (vinyl coated metal).

for individual materials and finite element analysis. The results of tensile tests and rectangular deep drawing simulations conducted using the defined numerical model of VCM were compared to experimental results to verify the suitability of the numerical model. VCM fracture mechanisms were identified through transverse strain investigations. The damage behavior of VCM materials during a bending process was examined using the verified numerical model. The formability of VCM materials was evaluated through Nakazima dome test (Nakazima and Kikuma, 1967; Nakazima et al., 1968). The material behavior of adhesive layers was expressed with perfect plasticity and GTN damage model simulations for drawing up forming limit curves.

2. Numerical method

2.1. Material model

In this study, GTN damage model was implemented with ABAQUS/Explicit. GTN damage model uses void volume fractions inside materials to mainly express metal damage and breakage but can be also applied to polymer materials (Chu and Needleman, 1980). Since VCM consists of metal and polymer materials, GTN damage model was judged appropriate to be used. The algorithm of GTN damage model is as follows.

The yield function of GTN model first proposed by Gurson and expanded by Tvergaard and Needleman is as shown by Eq. (1).

$$\Phi = \left(\frac{q}{\sigma_Y}\right)^2 + 2f^* q_1 \cosh\left(\frac{3}{2}q_2\frac{p}{\sigma_Y}\right) - \left(1 + q_3 f^{*2}\right) = 0 \tag{1}$$

where, σ_{rY} is materials' flow stress and is as shown by Eq. (2.a). K_0, ϵ_o, and n are strength factor, offset strain, and hardening coefficient respectively (Swift's model). In addition, $\bar{\epsilon}^{\mathrm{pl}}$ is the effective plastic strain as shown in Eq. (2.b) where ϵ_1, ϵ_2, and ϵ_3 mean the plastic strain. Also, the elastic behaviour is assumed that has linear deformation against the stress. Therefore, it can be expressed by the Hooke's law with the Young's Modulus.

$$\sigma_Y = K\left(\epsilon_0 + \bar{\epsilon}^{\mathrm{pl}}\right)^n \tag{2.a}$$

$$\mathrm{d}\bar{\epsilon}^{\mathrm{pl}} = \sqrt{\frac{2}{3}\left(\mathrm{d}\epsilon_1^2 + \mathrm{d}\epsilon_2^2 + \mathrm{d}\epsilon_3^2\right)} \tag{2.b}$$

q_1, q_2, and q_3 are constants proposed by Tvergaard through experiments as suitable ones for metal materials and $q_1 = 1.5$, $q_2 = 1.0$, and $q_3 = {q_1}^2$. q and p are effective stress and hydrostatic stress respectively and are expressed by Eq. (3.b) and (4) respectively. s_{ij} is the deviatoric stress tensor as shown in Eq. (3.a) where p is element of hydrostatic stress. δ_{ij} is the Kronecker delta, and $\boldsymbol{\sigma}$ means the stress tensor.

$$s_{ij} = \sigma_{ij} - p\delta_{ij} \tag{3.a}$$

$$q = \sqrt{\tfrac{3}{2}s_{ij}s_{ij}} \tag{3.b}$$

$$p = \tfrac{1}{3}\mathrm{trace}(\sigma) \tag{4}$$

f^* is a function of void volume fractions (f) which is a value proposed by Tvergaard and Needleman. f^* reflects rapid increases of void volume fractions after the critical void volume fraction f_c due to void coalescence and growth and is expressed by Eq. (5).

$$f^* = \begin{cases} f & \text{if } f < f_c \\ f_c + \bar{f}\left(f - f_c\right) & \text{else if } f \geq f_c \text{ and } f < f_F \\ f_u & else \end{cases} \quad \text{with } \bar{f} = \frac{f_u - f_c}{f_F - f_c} \tag{5}$$

where, f_F is the void volume fraction at the time of fracture. f_u is defined as $1/q_1$. Void volume fraction increment $\mathrm{d}f$ can be expressed as the sum of increments by void nucleation and increments by void growth as shown by Eq. (6). Void nucleation increments as shown by Eq. (7) can be expressed as the product of effective plastic strain increment $\mathrm{d}\bar{\epsilon}^{\mathrm{pl}}$ and variable A defined by Eq. (8). Variable A is a value proposed by Chu and Needleman (1980) and is expressed as the normal distribution function of effective plastic strain as shown by Eq. (8).

$$\mathrm{d}f = \mathrm{d}f_{\mathrm{nucleation}} + \mathrm{d}f_{\mathrm{growth}} \tag{6}$$

$$\mathrm{d}f_{\mathrm{nucleation}} = A\mathrm{d}\bar{\epsilon}^{\mathrm{pl}} \tag{7}$$

$$A = \frac{f_N}{s_N\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{\bar{\epsilon}^{pl} - \epsilon_N}{s_N}\right)^2\right) \tag{8}$$

In Eq. (8), ϵ_N, s_N, and f_N are the mean value, standard deviation, and volume fraction of void nucleation. Nucleation equations are calculated only under the condition of hydrostatic tension. In GTN model, the increments of microscopic equivalent plastic strain, $\mathrm{d}\bar{\epsilon}^{\mathrm{pl}}$, can be expressed according to microscopic and macroscopic equivalent plastic, $\mathrm{d}\boldsymbol{\epsilon}^{\mathrm{pl}}$, work as shown by Eq. (9). $\mathrm{d}\bar{\epsilon}^{\mathrm{pl}}$ is plastic strain increments.

$$\mathrm{d}\bar{\epsilon}^{\mathrm{pl}} = \frac{\boldsymbol{\sigma} : \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{pl}}}{(1-f)\sigma_Y} \tag{9}$$

Increments according to void growth considering volume changes of materials are expressed as shown by Eq. (10).

$$\mathrm{d}f_{\mathrm{growth}} = (1-f)\,\mathrm{trace}\left(\mathrm{d}\epsilon^{\mathrm{pl}}\right) \tag{10}$$

2.2. Finite element model

VCM consists of largely four materials; GI steel, PET film, PVC film, and adhesive layer. The largest defects occurring during forming processes are PET film damage and delamination and these

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