Journal of Materials Processing Technology 220 (2015) 146–156

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Prediction of delamination and tearing during stamping of polymer-coated metal sheet

Young-Ki Son[a], Dae-Cheol Ko[b], Byung-Min Kim[c,*]

[a] Precision Manufacturing Systems Division, Pusan National University, 30 Jangjeon-Dong, Busan, Gumjeong-Gu 609-735, South Korea
[b] Industrial Liaison Innovation Center, Pusan National University, 30 Jangjeon-Dong, Busan, Gumjeong-Gu 609-735, South Korea
[c] School of Mechanical Engineering, Pusan National University, 30 Jangjeon-Dong, Busan, Gumjeong-Gu 609-735, South Korea

ARTICLE INFO

Article history:
Received 7 April 2014
Received in revised form 6 January 2015
Accepted 16 January 2015
Available online 24 January 2015

Keywords:
Defect diagram
Delamination
Tearing
Two-layer FE model

ABSTRACT

The objective of this study is to design a stamping process for polymer-coated metal (PCM) sheets to prevent defects such as delamination and tearing. A defect diagram composed of the delamination limit curve and the tearing limit curve of the PCM sheet is developed for determining the safe region. Similar to the forming limit diagram, the defect diagram is constructed using the critical major and minor strains at which defects occur in various deformation modes. Experiments are performed for establishing the defect diagram of the PCM sheet by means of the limit dome height test and square cup deep-drawing test. A cross-hatched specimen is employed for estimating the delamination of the polymer layer from the steel substrate. Based on the defect diagram, a finite element analysis (FEA) of the stamping process is conducted to determine a forming condition without delamination and tearing. The effectiveness of the stamping process designed on the basis of the developed defect diagram is verified by a forming experiment. Comparison of the FEA results and experimental results reveals that the defect diagram is efficient and suitable for the design of the actual stamping process using PCM sheets.

1. Introduction

In the manufacturing process of outer panels of household appliances, most of the parts are formed from sheet metal into the required final shape. The panels are then coated with paint and subsequently subjected to a curing process. Vayeda and Wang (2007) reported that the conventional paint coating cycle can generate harmful substances such as volatile organic compounds (VOCs) or hydrocarbons. Various laws and acts have been passed by governments worldwide in an attempt to prevent pollution resulting from the paint curing and coating industry.

Polymer-coated metal (PCM) is an alternative material that can reduce VOC emissions and prevent the generation of hazardous wastes in the paint coating process. The polymer coating process is a continuous and automated process that is performed prior to the stamping process of a metal sheet. PCM has several advantages over most paint-coated metals, such as low friction, corrosion prevention, and excellent glossy appearance (Kalpakjian and Schmid, 2001; Levendusky et al., 1999). Furthermore, the polymer coating increases the resistance of the metal to corrosion. This allows the use of cold-rolled steel instead of stainless steel, which in turn reduces the material cost.

In spite of these advantages of PCM, its use has been limited by defects in the polymer coating that arise during the stamping process, which converts the sheet metal into a final product. For example, the PCM has to be free from delamination, as shown in Fig. 1(a). In other words, the adhesive bonding between the coating layer and the steel substrate must hold during the stamping process. Otherwise, tearing may occur on the coating layer as shown in Fig. 1(b). Therefore, the stamping process of PCM should consider not only the forming limit of the steel substrate but also how to prevent the delamination and tearing of the coating layer.

2. Previous research efforts

Delamination of PCM leads to the exposure of the steel substrate to the external environment. Therefore, delamination can potentially cause significant corrosion and weaken the steel substrate. If it can be predicted accurately, the process variables of the stamping process can be adjusted before the occurrence of delamination. Most prior research aimed at investigating the delamination of PCM has focused on the interfacial bonding strength. For example, Van den Bosch et al. (2006) used a cohesive zone model to describe

* Corresponding author. Tel.: +82515102319.
E-mail addresses: hiphoprnb@naver.com (Y.-K. Son), dcko@pusan.ac.kr (D.-C. Ko), bmkim@pusan.ac.kr (B.-M. Kim).

http://dx.doi.org/10.1016/j.jmatprotec.2015.01.013
0924-0136/

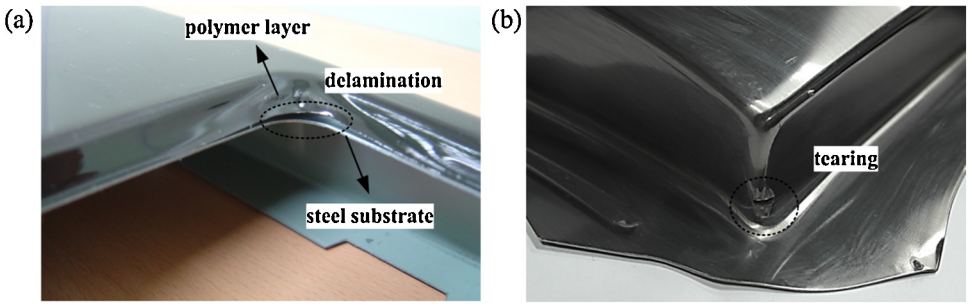

Fig. 1. Defects of PCM sheet. (a) Delamination and (b) tearing.

the interface of PCM. Van den Bosch et al. (2009) described the development and application of a numerical model that can predict the delamination of the polymer coating from a steel substrate during deep-drawing. A test method termed the notched coating adhesion test was proposed for estimating the adhesive performance and durability by using special specimens that accelerate humidity conditioning (Chang et al., 1999). The specimens were subjected to uniaxial tensile strain, and the strain at which the coating debonded was used to calculate the critical strain energy release rate. Vayeda and Wang (2007) evaluated the durability of PCM under plastic deformation. A number of tests were conducted, including the tensile test, rectangular stretch bend test, and tape pull test. The parts were inspected for coating durability under various environmental conditions such as the presence of moisture and salt. However, because these tests consider only one deformation mode, accurate prediction of the debonding of coatings in complex deformation modes on deformed substrates in the stamping process is not possible. Therefore, the delamination of coatings in various deformation modes needs to be considered, such as deep-drawing, uniaxial tension, plane strain, and biaxial tension. Some recent studies have addressed the pretreatment and chemical composition of a steel substrate. For example, Hatanaka et al. (1989) investigated coating adhesion after the deep-drawing process in relation to the pretreatment of aluminum. They concluded that the deterioration in adhesion by deep-drawing was due to the cohesive failure of films, which resulted from the pretreatment and the change in the underlying surface topography. Deflorian et al. (1999) evaluated the adhesion performance of polyurethane- and polyester-coated stainless steel after Erichsen cup drawing according to the composition of the substrate by using electrochemical impedance spectroscopy. Braunlich and Demmler, 1998 evaluated the formability of polymer-coated steels under production conditions such as bending, folding, embossing, and deep-drawing. Coated parts were inspected for gloss loss, coating tear-off, and other defects. Their study provided a method for evaluating coating performance. However, the use of this method for the coating and substrate is expensive and time-consuming. Thus, it is desirable to use simple test methods for evaluating the delamination limit of coatings.

In light of the increasing interest in deformable coated metal, coating defects such as tearing, tiny cracks, and scratches on PCM have garnered research attention. Jaworski et al. (1999) studied the application of PCM to strip ironing. Their experiments demonstrated that the coating integrity was affected by tool design and process conditions. Huang (2001) and Huang et al. (2001) further explored the effects of temperature on the survivability of coatings in strip ironing. Selles et al. (2008) investigated the effects of process parameters on the ironing of three-layered PCM, with the aim of obtaining a product with a high surface quality. In their study, the process parameters were evaluated based on their influence on the surface quality factor. Ramsteiner et al. (2003) investigated the scratch resistance of polymer coatings through a needle test and converted the obtained data to a failure map. However, all these studies focused on tribological aspects such as wear with high-pressure contact, excellent appearance achieved by strip ironing, and scratches. They were thus unable to account for the delamination and tearing defects that arise as a result of deformation during the stamping process. Therefore, a powerful and effective method for designing a stamping process is required in order to manufacture a product made of PCM that is free of delamination and tearing. A simulation technique is also required for applying the defect criterion.

Therefore, the objective of this study is to develop a defect diagram for the prediction of delamination and tearing in the stamping process of a PCM sheet. Similar to the forming limit diagram (FLD), the defect diagram plots the delamination limit curve (DLC) and the tearing limit curve (TLC), and these curves are drawn on the critical major and minor strain axes. The DLC is constructed by plotting the set of critical strains of the steel layer when the polymer coating peels off from the substrate. The TLC is constructed by plotting the set of critical strains of the polymer coating layer when tearing occurs. The limit dome height (LDH) test and square cup deep-drawing test are performed to obtain the DLC and TLC in various deformation modes such as deep-drawing, uniaxial tension, plane strain, and biaxial tension (Marciniak et al., 1992). The developed defect diagram is applied to the design of the stamping process of the PCM sheet by finite element analysis (FEA). A two-layer finite element (FE) model is used for modeling the steel substrate and polymer coating, and the tied condition is applied at the equivalent nodes of each layer. The effectiveness of the stamping process designed by the defect diagram and the two-layer FE model is then verified experimentally.

3. Material properties

The structure of the PCM sheet employed in this study is shown in Fig. 2(a). It consists of three different layers: the substrate, a polyvinyl chloride (PVC) layer, and a polyethylene terephthalate (PET) layer. The initial thickness of each layer is measured by a scanning electron microscope (SEM), as shown in Fig. 2(b). A single side on the 800-μm-thick steel substrate is coated with the polymers. The thicknesses of the PVC and PET layers are measured as being 60 μm and 30 μm, respectively. The true stress–true strain response of the steel is shown in Fig. 3(a).

Tensile tests of the polymer coating are performed according to the ASTM D882, 2012 at room temperature in order to evaluate the mechanical properties of each layer. These properties are shown in Fig. 3(b). Although the protective film serves to prevent surface scratches of the PET film during transportation, the mechanical properties of this film are not considered in this study.