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Delamination in deformed polymer laminated sheet metals

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ABSTRACT

Polymer laminated sheet metal (PLSM) is a layered material in which a thin polymer film is bonded to a sheet metal substrate by means of an adhesive layer. The PLSMs could potentially be used as the blank materials for forming applications such as sheet drawing and stamping. Due to the difference in formability of metallic and polymeric components in the PLSMs, deformation of these materials induces residual stress in the polymer adherend involving thin film and adhesive layer. The residual stress, consequently, may cause interfacial delamination of polymer adherend and hence limit forming applications of the PLSMs. This paper presents an experimental method based on shear punching of uniaxially deformed PLSMs for the assessment of interfacial delamination between metallic substrate and polymer adherend. The experimental results show that the interfacial delamination depends on the amount of deformation and type of the polymer adherend material. In addition, it is shown that the deformation-induced delamination at the interface between the polymer adherend and metallic substrate is a retardation process and can be characterized by the three-parameter Voigt rheological model. Beyond the capabilities of the experiment, the Voigt model can estimate the amount of pure elastic delamination, which occurs immediately upon load removal after deformation.

1. Introduction

Polymer laminated sheet metals (PLSMs) are a class of bonded sheet materials, which are produced by adhering a polymer film to a metallic sheet surface using an adhesive layer. The PLSMs are in use in different industries, such as automotive, aerospace, food, decoration, etc. These materials also offer potential to be used as the blank materials for forming sheet components for above industries. They have advantages over bare metallic sheets, which are typically subjected to painting and/or finishing after forming. The reduction of the number of process steps (such as paint curing of stamped automotive panels) and therefore reduction in volatile organic compound (VOC) emissions result in more environmentally friendly manufacturing. However, forming of the PLSMs may deteriorate interfacial adhesion, thereby limiting their use in the as-formed state [1–4]. The differences in deformation behavior of the constituents (sheet metal, adhesive and polymer film) in the PLSM structure is a primary reason for loss of adhesion.

Deformation of the PLSM results in two simultaneous consequences: first, the development of the residual stresses in polymer adherend[1] and second, the evolution of the surface roughness of metallic substrate. These consequences could either benefit or harm interfacial adhesion depending on how they act toward enhancing or deteriorating the bond between the constituents. In an ideal case, the energy stored in the adherend material due to the existence of tensile residual stress should be lower than the adhesion energy due to the contact between the bonded materials; ensuring that the adherend materials do not delaminate after deformation. Increasing the area of contact between bonded materials is beneficial to interfacial adhesion [5,6]. On the other hand, the increase in tensile residual stresses promotes interfacial delamination [7].

The energy due to the imposed stresses is stored or dissipated through the change in microscopic features in the polymer adherend [8] (e.g., molecular arrangement in polymer, molecular chain elongation, etc.) while the substrate surface roughness changes interfacial adhesion energy between contacting materials (sheet metal and adhesive).

For measuring residual stresses at a macro scale, i.e., larger than microscopic features, the assessment techniques can be classified as non-destructive, semi destructive and destructive methods [9,10]. Non-destructive methods such as diffraction techniques are based on the

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Abbreviations: PLSM, polymer laminated sheet metal; PSA, pressure sensitive adhesive; VOC, volatile organic compound; PE, Polyethylene; PP, Polypropylene; PVC, polyvinyl chloride; HSP, hole shear punching

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[1] Polymer adherend as a term refers to the combination of a polymer film and an adhesive layer.

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comparison between the physical properties in stressed and stress-free regions in the components. The semi-destructive and destructive methods rely on releasing residual stresses by removing the material from stress-carrying component followed by the displacement measurement after material removal.

The hole drilling method [11] is one of standardized destructive techniques applicable for determination of residual stress in layered materials. For the PLSMs, however, this technique needs to be modified because the heat generation during the hole drilling operation will locally melt the polymer adherend adjacent to the hole and thus prevents accurate determination of residual stresses. Also, heat-affected zone is not localized to the hole edge and therefore influences overall amount of residual stresses. Even using a coolant, during the hole drilling process, cannot satisfactorily resolve this issue. In the present work, to overcome the limitations of the hole drilling method, a technique of hole shear punching (HSP) is explored for assessing the effect of residual stresses on interfacial delamination after uniaxial tensile deformation of the PLSMs. In the HSP method, a sharp radius punch is utilized to shear the sheet specimen that is clamped around the periphery using a die and a blank holder. As a result, a circular specimen (or slug) of the material is separated directly below the punch. This slug can be used for measuring relative displacement (or interfacial delamination induces by tensile residual stress) between the sheet metal and the polymer adherend materials. In contrast to the hole drilling method, the effects of heating, drilling speed and cooling mediums on delamination are minimized or eliminated by utilizing the HSP method.

The interfacial delamination of the polymer adherend after deformation is a time-dependent phenomenon. Since the polymer adherend behaves as a viscoelastic material, delamination occurs over a time period comparable with experimental time scale [12]. Time-dependent responses such as creep and stress relaxation of viscoelastic materials have been dealt with in the literature [8,13–15]. For analyzing and mathematical description of this type of behavior, one commonly used approach is mechanical (rheological) modeling. In the present study, the standard three-parameter Voigt rheological model [14] is used to describe the time dependency of the polymer adherend delamination after uniaxial tensile deformation of the PLSMs.

2. Experimental procedure

2.1. Materials and PLSM preparation

Three types of PLSMs in the form of strips were prepared by laminating one side of the bright-annealed stainless steel (AISI-430) strips using a roll laminator (Chemsultants International-Model HL-100) at 23 °C. The sheet metal substrate dimensions were 100.0 mm in length; 25.4 mm in width and 0.6 mm in thickness (see Fig. 1 for a schematic of the PLSM strip). The samples length was along rolling direction of the sheet metal.

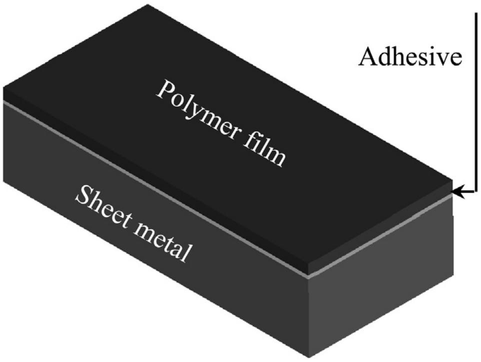

Fig. 1. A schematic of the PLSM strip.

Table 1
3M polymer films and adhesives.

Adherend name	Polymer film [a]	PSA [a] (Acrylic type)
A	PE/PP copolymer + PET coat	High tack, medium shear
B	PE/PP copolymer + PET coat	High shear, medium tack
C	PVC	High shear, medium tack

[a] The thickness of polymer film and PSA layer were 0.091 mm and 0.036 mm, respectively.

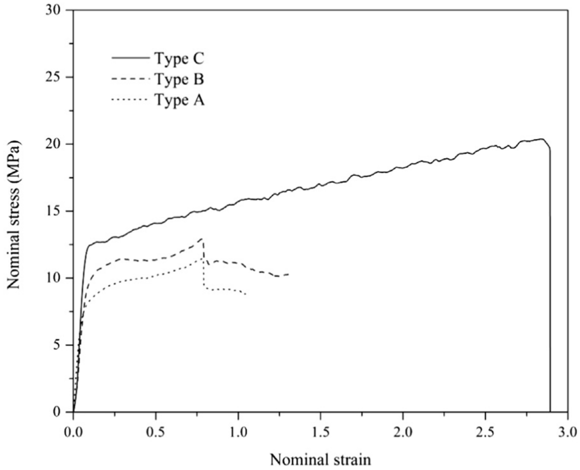

Fig. 2. Uniaxial tensile stress – strain curves of polymer systems at 2 mm/min crosshead speed. The drop in nominal stress at about 0.75 nominal strain for adherends A and B is due to the PET coat rupture.

The details of composition of the polymer adherends (films with pre-applied adhesive) used in this study are presented in Table 1. Two different types of polymer adherend involved either the same polymer film or adhesive type. The A and B adherend types involved different types of acrylic pressure sensitive adhesive (PSA) layer with high tack and high shear properties, respectively. Both of these adherends involved a Polypropylene (PP) and Polyethylene (PE) copolymer layer, which was sandwiched between a high gloss Polyethylene Terephthalate (PET) coat and the adhesive layer. The C type of the adherend materials had same type of adhesive as type B but applied to a PVC film. All three adherends had same film thickness of 0.127 mm and the adhesive layer thickness of 0.036 mm. Fig. 2[2] shows nominal stress-strain curves for three adherend materials obtained from uniaxial tensile test experiment conducted at 2 mm/min crosshead speed using an INSTRON tensile machine (Model 3366) with a ± 500 N load cell. The drop in nominal stress at about 0.75 nominal strain for adherends A and B is due to the PET coat rupture that was considered as a failure point of these adherends.

2.2. PLSM pre-straining[3] followed by HSP experiment

After lamination, the PLSM samples were held in vacuum bags at ambient temperature of 23 °C for four weeks to stabilize interfacial bonding before uniaxial pre-straining. After this dwell time, no delamination was observed for any type of the PLSMs. Three different uniaxial tensile strain values of 0.05, 0.11 and 0.19 were applied to each of the PLSM strips using a computer controlled servo-hydraulic MTS machine at the crosshead speed of 2 mm/min. Immediately after uniaxial straining, the samples were subjected to the HSP experiment symmetrically with respect to the length and width of the specimen and normal to the thickness direction at a punching rate of 5 mm/min. A

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[2] Uniaxial tensile test was conducted following the ASTM D-882 standard [16].

[3] Pre-strain refers to uniaxial tensile deformation applied to the PLSM prior to the HSP process.