ENGINEERING TRANSACTIONS • *Engng. Trans.* • **65**, 1, 53–59, 2017
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
National Engineering School of Metz (ENIM) • Poznan University of Technology

Macroscopic Response and Decohesion Models of Metal-Polymer Laminates

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Metal-polymer laminates are used in several technological fields, with applications ranging from flexible electronics to food packaging and lightweight components for transportation sectors. Models of different complexity have been proposed to evaluate the overall performances of these materials. Models are also used to recover the adhesion properties of the plies, which are difficult to be characterized otherwise. The overall material responses resulting from different constitutive assumptions are examined in this paper.

Key words: metal foils, polymers, laminates, adhesion, failure.

1. Introduction

Metal-polymer laminates are used in several technological fields, with applications ranging from flexible electronics to food packaging and lightweight components for transportation sectors. The actual material coupling is usually designed in order to meet different functional requirements, including the bearing of mechanical actions [1–4]. Specific features of these composites are small thickness of the layers, which may behave differently from the corresponding bulk materials, and wide deformability range of the polymeric core or support. These laminates can fail in a variety of modes, depending also on the adhesion level among the plies.

Models of different complexity have been proposed to evaluate the overall performances of these material systems. In addition, simulation models of experiments are also used to recover the adhesion properties of the plies, often characterized only indirectly.

The variety of observable responses resulting from different constitutive assumptions and the sensitivity to the model parameters of measurable quantities have been evaluated in a parametric study. Some results are reported in this paper.

2. The problem

Numerical and analytical approaches have been developed to evaluate the performances of thin metal-polymer laminates. The geometrical and mechanical properties of the bulk components in these material systems and the properties of the interfaces can vary to a large extent, also depending on the selected application [5–9]. The simple layered configuration shown in Fig. 2 is examined in this study.

A thin metal foil of thickness h is supported by a polymeric substrate of thickness H. The sample is stretched as it is typically done in tensile tests. The overall response of the laminate is simulated in the large strain and large displacement regime by a popular finite element (FE) code [10] in both plane stress and plane strain conditions. Quasi-static analyses are performed under displacement control using a numerical procedure with automatic step increment. The numerical model considers the cross-section of this material system subdivided into four-node elements with reduced integration scheme and hourglass control mode. The metal foil is discretized into almost square elements with a characteristic length $h/20$. The same mesh is defined for the polymer ply within the depth h from the interface, and the element size is then progressively increased. The same discretization rules are implemented in all the simulations in order to allow for a direct comparison among the numerical results.

An elastic-plastic constitutive law based on the classical Hencky-Huber-Mises yield criterion with exponential hardening rule is assumed for both bulk components, with a saturation level for the metal strength. The relevant constitutive parameters, listed in Table 1, are typical of aluminum (Al) foils and polyethylene (P) films employed in beverage packaging, already investigated in the former contribution [2]. The corresponding *true* stress versus *logarithmic* strain relationship under uniaxial loading is represented for both materials in Fig. 1.

The simulations assume either perfect continuity or imperfect adhesion between the laminate plies. Possible opening and sliding relative displacements induced by the external action are controlled by zero-thickness interface elements characterized by independent bi-linear traction-separation relationships, schematically represented in Fig. 4. Traction vanishes for large relative displacements to reflect the adhesive characteristics of the considered polymers.

Table 1. Constitutive parameters defining the uniaxial curves drawn in Fig. 1.

Material	Elastic modulus [MPa]	Poisson's ratio [–]	Yield limit [MPa]	Material strength [MPa]
Metal (Al)	45 000	0.3	35	72.5
Polymer (P)	200	0.3	6.5	–

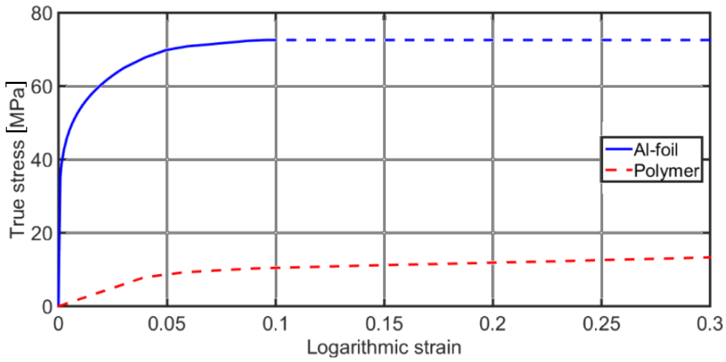

Fig. 1. Uniaxial bulk material response for the reference constitutive parameters listed in Table 1.

A parametric study is performed in order to understand the effect on the overall material response of the characteristics of the polymer support and of the interface properties, while the thickness $h = 9$ µm (typical reference value for beverage packaging applications) and the mechanical properties (elastic modulus E_{Al} and initial yield limit $\overline{\sigma}_0$) of the metal are fixed to the values listed in Table 1 in all the analyses.

3. Comparative results

The results discussed in this section refer to the numerical simulations carried out in plane stress conditions to reproduce the material status under tensile test, which is usually performed on narrow strips (15 mm wide, 100–180 mm long, see, e.g., [2]). The analyzed output consists of the measurable quantities, which are commonly recovered in experiments, namely: the *nominal* stresses versus the *engineering* strains, and the delamination length, if any.

The overall material responses recovered in the hypothesis of perfect continuity among the plies are summarized by the curves drawn in Fig. 2. The graphs refer to different values of thickness H and elastic modulus E_{P} of the polymer support, in the wide range indicated in the figure. It can be seen that the metal layer provides a significant contribution to the overall load carrying capacity for small H/h ratios.

The increased effective strength is however accompanied by the apparent brittleness of the laminate response, although hardening plasticity has been assumed for both components at constitutive level. The overall softening shown in Fig. 2, and already documented in [2], is in fact induced by the strong material thinning associated with the large plastic strains experienced by both bulk materials.

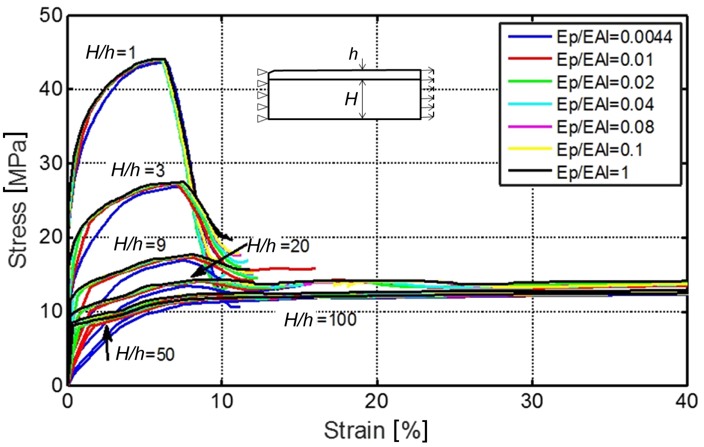

Fig. 2. Nominal stress versus engineering strain values in the hypothesis of perfect continuity at the interface among the plies.

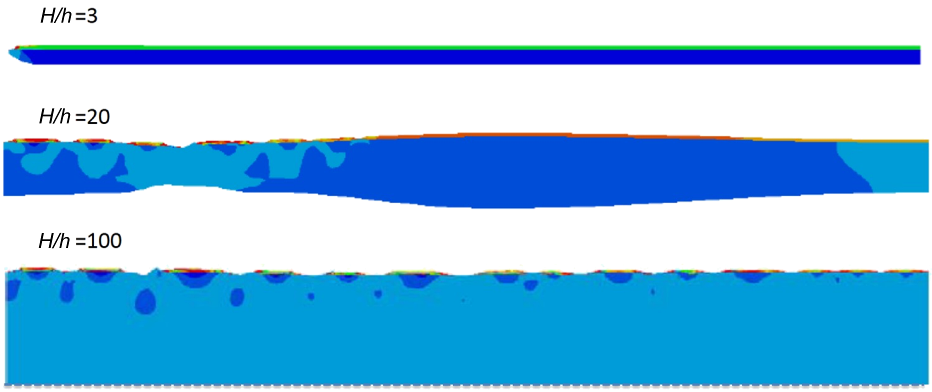

Fig. 3. Deformation modes recovered in the hypothesis of perfect adhesion.

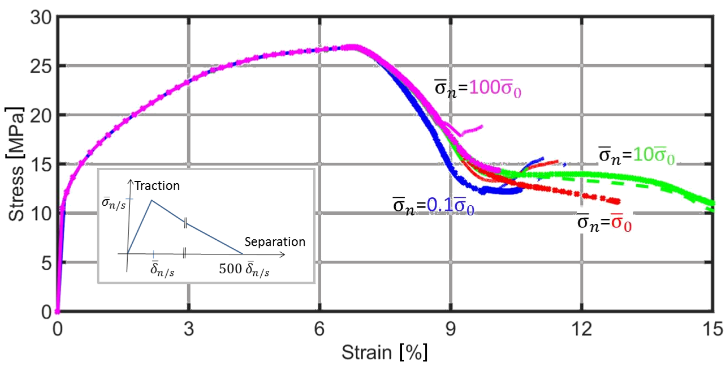

Fig. 4. Nominal stress versus engineering strain values in the hypothesis of imperfect adhesion at the interface among the plies ($H/h = 3$).

The performed analyses show that a necking is initiated in correspondence to the section where a slight reduction of the metal thickness has been introduced in the simulation model. The localized deformation is hence transferred to the polymer ply by the continuity at the interface, as shown in Fig. 3 for the case $H/h = 3$.

A rather different output is obtained for high H values. In this case, the stiffness of the support is capable to redistribute stresses and to produce a periodic strain localization pattern (shown in Fig. 3 for the case $H/h = 100$), which enhances the overall deformation capability. Similar results were obtained in [5] by perturbation analysis for the limit case of a steeply hardening polymer substrate of infinite thickness. Intermediate responses are recovered for other realistic H/h ratios.

The graphs in Fig. 2 also show that increasing the elastic modulus of the polymer of more than two orders of magnitude does not produce any significant effect.

The overall deformability of the investigated material systems may be improved by weak interfaces. In this case, the necking of the metal foil is accompanied by delamination, which permits the polymer support to expand to a larger extent although the likelihood of metal rupture is enhanced (see, e.g., [6] and [7]).

The graphs in Fig. 4 summarize the response of the laminate with adhesive connection between the layers, for the ratio $H/h = 3$ and the bulk material properties listed in Table 1. In the analyses, the maximum stresses transferable at the interface in normal and tangential direction ($\overline{\sigma}_n$ and $\overline{\sigma}_s$, respectively) have been prescribed independently, equal to 0.1, 1, 10 and 100 times the initial yield limit of the metal, $\overline{\sigma}_0$. The initial slope $\overline{\sigma}_n/\overline{\delta}_n$ (equal to $\overline{\sigma}_s/\overline{\delta}_s$) of the bilinear traction-separation law visualized in Fig. 4 assumes the value 38.9 kN/mm^3 (such that $\overline{\delta}_{n/s} = 0.1h$ when $\overline{\sigma}_{n/s} = \overline{\sigma}_0$). Colors identify the interfacial strenght in the normal direction, while the response obtained for different shear strengths is represented by a different line type. The tails of the nominal stress versus the engineering strain curves drawn in Fig. 4 show the residual strength associated with the deformation in the polymer support, which does not experience strain localization.

The graphs are otherwise similar to those recovered for the same thickness ratio in the case of perfect displacement continuity, shown in Fig. 2. The normal interfacial strength has little influence on the slope of the softening branch, almost unaffected by the shear characteristics. In the situations characterized by intermediate adhesion properties, the interface parameters of the considered material system have a weak influence also on the failure mode, although the combination with different bulk material properties may lead to diverse situations.

4. Closing remarks

The failure mode of metal-polymer laminates is controlled by the interplay between decohesion and strain localization phenomena, depending on the characteristics of the material coupling. The overall load carrying capacity of the composite system analyzed in this contribution is defined by the necking phenomena occurring in the metal foil and, therefore, by the relevant constitutive properties, while the interface characteristics affect mainly the post-peak deformability.

The plane stress results discussed herein are qualitatively similar to those obtained in plane strain state, closer to common operating conditions of the laminates, with effective strength increased by stress triaxiality. The output of the performed simulations is expected to be influenced by discretization details to the same extent of imperfections in real experiments. However, the general trends inferred from the present study help in understanding the sensitivity of measurable quantities to constitutive and interface parameters, showing the difficulties associated with the development of effective parameter identification procedures.

References

1. Wong W.S., Salleo A. (Eds.), *Flexible electronics. Materials and applications*, Springer, New York, 2009.

2. Bolzon G., Cornaggia G., Shahmardani M., Giampieri A., Mameli A., *Aluminum laminates in beverage packaging: models and experiences*, Beverages, **1**(3): 183–193, 2015, doi: 10.3390/beverages1030183.

3. Andreasson E., Kao-Walter S., Ståhle P., *Micro-mechanisms of a laminated packaging material during fracture*, Engineering Fracture Mechanics, **127**: 313–326, 2014, doi: 10.1016/j.engfracmech.2014.04.017.

4. Grujicic M., Sellappan V., Omar M.A., Seyr N., Obieglo A., Erdmann M., Holzleitner J., *An overview of the polymer-to-metal direct-adhesion hybrid technologies for load-bearing automotive components*, Journal of Materials Processing Technology, **197**(1–3): 363–373, 2008, doi: 10.1016/j.jmatprotec.2007.06.058.

5. Li T., Huang Z.Y., Xi Z.C., Lacour S.P., Wagner S., Suo Z., *Delocalizing strain in a thin metal film on a polymer substrate*, Mechanics of Materials, **37**(2–3): 261–273, 2005, doi: 10.1016/j.mechmat.2004.02.002.

6. Li T., Suo Z., *Ductility of thin metal films on polymer substrates modulated by interfacial adhesion*, International Journal of Solids and Structures, **44**(6): 1696–1705, 2007, doi: 10.1016/j.ijsolstr.2006.07.022.

7. Xu W., Lu T.J., Wang F., *Effects of interfacial properties on the ductility of polymer-supported metal films for flexible electronics*, International Journal of Solids and Structures, **47**(14–15): 1830–1837, 2010, doi: 10.1016/j.ijsolstr.2010.03.017.

8. Lu N., Suo Z., Vlassak J.J., *The effect of film thickness on the failure strain of polymer supported metal films*, Acta Materialia, **58**(5): 1679–1687, 2010, doi: 10.1016/j.actamat.2009.11.010.

9. Mróz Z., Mróz K.P., *Analysis of delamination and damage growth in joined bi-layer systems*, Geomechanics for Energy and the Environment, **4**: 4–28, 2015, doi: 10.1016/j.gete.2015.10.001.

10. Abaqus/Explicit, Release 6.13-1, Dassault Systems Simulia Corp., Providence, RI, USA, 2013.

Received October 14, 2016; accepted version November 17, 2016.