International Journal of Adhesion & Adhesives 40 (2013) 49–55

Contents lists available at SciVerse ScienceDirect

International Journal of Adhesion & Adhesives

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

Prediction of coating adhesion loss due to stretching

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ARTICLE INFO

Article history:
Accepted 30 June 2012
Available online 25 July 2012

Keywords:
Polymer coating
Plastic deformation
Interfacial fracture mechanics
Adhesion loss

ABSTRACT

Polymer coated sheet metals are widely used for part fabrication in industry. To ensure that the manufactured products can meet the service life requirement, the effect of plastic deformation on coating adhesion is a critical concern. This paper presents an investigation of coating adhesion loss in forming polymer-coated sheet metals. A set of experiments were conducted to evaluate the pull-off strength of coatings before and after uniaxial stretching. The experiments show that axial plastic deformation can cause adhesion to deteriorate. An analytical method based on a virtual interface crack model was developed to evaluate the adhesion potential and was used to quantitatively predict the adhesion loss of two polymer coated sheet metals. The prediction results are in good agreement with the experimental measurements. A parametric study was also conducted to investigate the effects of material properties and coating/substrate thickness on adhesion loss. The results of this study can be used to attain better product design and application development for polymer coated sheet metals.

1. Introduction

Sheet metal has diverse applications in various industries such as automotive, packaging, appliance, construction, and consumer products. Parts fabricated from sheet metal are generally coated with polymer coating for functional, surface protection, and decoration purposes. The traditional manufacturing processes for sheet metal involve the sequence of forming sheet metal into a desired shape followed by the application of coating or paint. The polymer resin in coating is delivered by dissolving the polymer in a carrier fluid. After coating is applied, parts are then placed in an oven for the coating to cure. The organic solvent contains toxic substances, and in many cases, gaseous volatile organic compounds (VOCs) are generated during curing. The process also produces large amount of waste water. As a result, such a coating process becomes a serious environmental concern [1].

An efficient alternative is to use pre-painted materials from sheets or coil coating for metal forming processes. The coil coating process could reduce VOCs emissions and prevent the formation of hazardous wastes with its highly automated and continuous process [2,3]. The coating thickness can be accurately controlled during the process, which ensures consistent chemical and mechanical properties of the coating. Compared to the batch type of post-forming painting process, the coil coating provides a higher quality of coating adhesion and a variety of coating types, while resulting in less impact on the environment [4,5]. Although some manufacturers are converting from post-forming painting to forming pre-coated metal sheets for part fabrication, maintaining coating surface integrity and adhesive bond after forming remains a major technical challenge. In forming pre-coated (from sheet or coil coating) sheet metal, adhesion loss along coating–substrate interface under plastic deformation can be a critical concern.

Interface crack between two infinite elastic bodies under edge loading was first investigated by Suo and Hutchinson [6]. A review of elasticity solutions for cracks in layered materials was presented later [7] to address issues in mixed mode elastic fracture phenomena. An application of such work is the analysis of interface cracking driven by residual stress in layered material such as highly dissimilar materials in electronic packages [8]. Another application of the solution in [6] is the analysis of interface fracture toughness. To evaluate bonded joint structures subjected to combined loading, a fracture criterion based on the principal strain and the hydrostatic tension was proposed. It was shown that the model prediction correlated well to some of the experimental results [9]. Banks-Sills and Ashkenzai [10] presented a methodology for measuring interface fracture properties of composite materials. Several criteria for interface fracture were then examined and compared to test results [11]. To better predict the pull-off loads of an adhesive joint, non-linear adhesive properties were incorporated into numerical models [12]. Characterization of interfacial fracture of adhesive joint in mixed-mode loading was also reported [13].

For elastic–plastic solids, an idealized traction–separation law was proposed by Tvergaard [14] to characterize crack growth and

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http://dx.doi.org/10.1016/j.ijadhadh.2012.07.007

interface fracture. The influence of plasticity on mixed mode interface toughness was further investigated [15,16]. It was reported that plasticity enhances the interface toughness for all modes of loading. From a different angle, effects of plasticity and segregation on interface adhesion were presented by Evans et al. [17]. The fracture process was represented in terms of a cohesive zone model where fracture is determined by the work of separation and the peak stress [14].

It is clear that debonding between coating and substrate can be analyzed by using fracture mechanics models. Dillard et al. used a notched coating adhesion test with pre-conditioned samples loaded in tension to measure the interfacial fracture toughness of coatings [18]. With tensile loading, the pull-off test such as PosiTest [19–21] can provide quantitative evaluation of adhesion strength. Using pull-off test, Lee and Kim [22] investigated coating failure due to moisture penetration to the bonding interface for oil tanker applications. Similarly, adhesive strengths of different powder coated aluminum sheets were evaluated using the pull-off test [23]. As can be observed, these investigations deal with coating delamination with no or little substrate plastic deformation.

To characterize the adhesion affected by plastic bending, a modified shear test [24] was used to investigate the interface adhesion of laminated sheets under v-bending. The interface adhesion of polymer coated metal sheet during plastic deformation was examined by using the cohesive zone model in numerical simulation of the deformation process [25]. The work emphasized on the evolution of polymer behavior and the evolution of roughness of the metal that could influence the polymer–metal adhesion. A mixed numerical–experimental approach was adopted to investigate delamination in polymer coated steel [26]. An extended cohesive zone model was proposed for large deformation. To obtain the interfacial properties for numerical simulation, an inverse parameter identification procedure was used. Further development of the numerical model and application of the model predicting delamination during deep-drawing of polymer coated metal sheets were reported in [27].

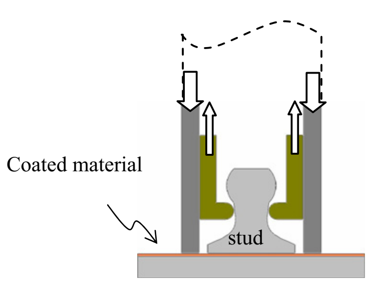

Fig. 1. A pull-off tester with manual hydraulic pump and a selfalignment stud [19].

It can be observed that most of the previous work attempted to determine the interface fracture toughness or to calculate the stress (or loading) required to cause debonding. As coated sheet metals could be deformed without apparent delamination, damage at the polymer–metal interface could lead to a decreased service life. The objective of the present work is to quantitatively determine the adhesion loss due to substrate plastic deformation. In this paper, a virtual crack model is proposed to analyze the polymer–metal interface and to predict coating adhesion loss after deformation. The model predictions are compared to the experimental results. Based on the developed model, a parametric study is also reported.

2. Experiments

The coating adhesion loss can be determined by measuring the coating pull-off stresses on specimens before and after deformation. The pull-off tests are conducted following the ASTM D4541-90 procedure [20] using a PosiTest adhesion tester as shown in Fig. 1 [19]. The testing procedure involves attaching a metal stud on the coating surface with glue and up-lifting the metal stud by a hydraulic pump. As the lifting action is slow and at a constant rate, the rate effect on coating adhesion is not evaluated while using this testing procedure.

To measure the pull-off stress after plastic deformation of the coated-sheet, the deformed specimen must have a flat area for metal studs to attach. The specimen for the present investigation is modified standard uniaxial tensile test specimen. The center area (gage length) is designed to fit two 10 mm diameter metal studs. The specimens can be stretched into different strain levels, and the maximum strain that can be attained before fracture depends on the mechanical property of the metal substrate. The deformation is obtained by using a uniaxial tensile testing machine with displacement control. While the pull-off test is conducted on the top side of the specimen, square grids are created on the back side of coated sheet for strain measurement as shown in Fig. 2(a). An optical microscope with an X–Y table is used to measure the grid size after deformation, and the major (longitudinal) and minor (transverse) strains are calculated from the changes in grid size as shown in Fig. 2(b).

As glue is used to attach metal studs to the coating surface, there are six possible debonding modes: (1) adhesive failure between the glue and the metal stud, (2) cohesive failure of the glue, (3) adhesive failure between the glue and the coating, (4)

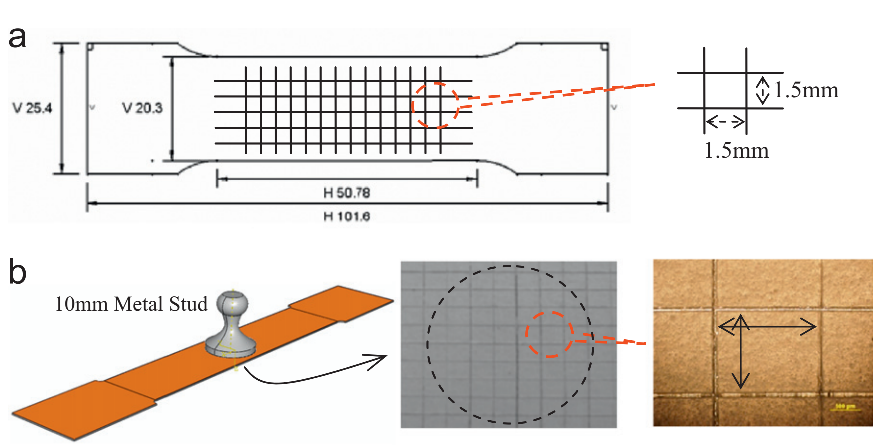

Fig. 2. A pull-off test specimen for applying uniaxial tension: (a) grids made on the back side of the specimen and (b) strain is measured from changes in grid size using an optical microscope.