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Numerical–experimental assessment of roughness-induced metal–polymer interface failure

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ABSTRACT

A numerical–experimental method is presented to study the initiation and growth of interface damage in polymer–steel interfaces subjected to deformation-induced steel surface roughening. The experimentally determined displacement field of an evolving steel surface is applied to a numerical model consisting of a polymer coating and interface layer. The measured displacement field is obtained with a Finite Element based Digital Image Correlation method.

The resulting simulations provide novel insights into the mechanical behaviour of the polymer–steel interface during interface roughening. The appearance of local hills and valleys on the evolving steel surface results in local bands of intensified stress in the polymer layer. These localized deformation bands trigger interface damage, which grows as the surface deformation increases. Polymer ageing initially delays the initiation of interface damage. However, for increased polymer ages the average interface damage increases. Likewise, the critical strain, at which the interface integrity is locally compromised, decreases.

The presented method allows for a detailed study of the interface integrity during deformation-induced steel surface roughening. With properly identified material parameters, it becomes possible to tailor the polymer–steel material properties to minimize interface damage during production and storage of cans or canisters, e.g. for food and beverages.

1. Introduction

1.1. Metal–polymer laminates

In recent years, metal–polymer laminates of electrolytic chromium coated steel (ECCS) sheets coated with a polymer layer (see Fig. 1(a)) have become increasingly popular for packaging of food and beverages. Producing cans or canisters from these pre-coated steels offers several advantages over the traditional production method. In the latter, a can is made from blank steel sheet after which it is lacquered with a protective coating on the inside and a decorative coating on the outside. Compared to this traditional production process the use of pre-coated packaging steel leads to a reduction of energy consumption and CO_2 emission with one third. Moreover, the process water used and the resulting solid wastes are reduced to practically zero (Van der Aa et al., 2000).

The use of polymer coated steels entails a number of challenges, since the coating is applied before the actual

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Abbreviations: ECCS, electrolytic chromium coated steel; FE-DIC, Finite Element based Digital Image Correlation; RD, rolling direction; TD, transverse direction; DRD, deep-draw, deep-redraw; EGP, Eindhoven Glassy Polymer.

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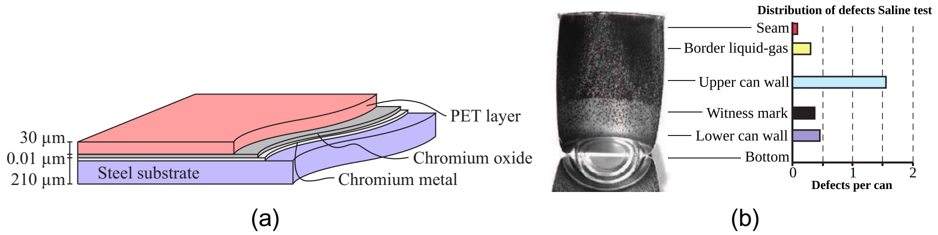


Fig. 1. (a) Different material layers in a polymer coated ECC steel (after Van den Bosch et al., 2008) and (b) experimentally observed interface damage (after Boelen et al., 2004).

can forming process. This implies that the coating undergoes the same deformation steps as the ECCS substrate, i.e. deep (re-) drawing (DRD) and wall-ironing. Large deformations are induced at high strain rates, pressures and temperatures. During this production process, the coating must fully adhere to the ECCS substrate. Boelen et al., 2004 have shown experimentally that damage is introduced at the interface during production and sterilization, see Fig. 1(b). After product fabrication, damage is often not visible for the human eye, however it becomes apparent during the prolonged shelf-life of the product. Application for food packaging demands a material that does not exhibit any visible or even measurable corrosion on the inside, even after a relatively long shelf-life period (Boelen et al., 2004; Van den Bosch et al., 2008).

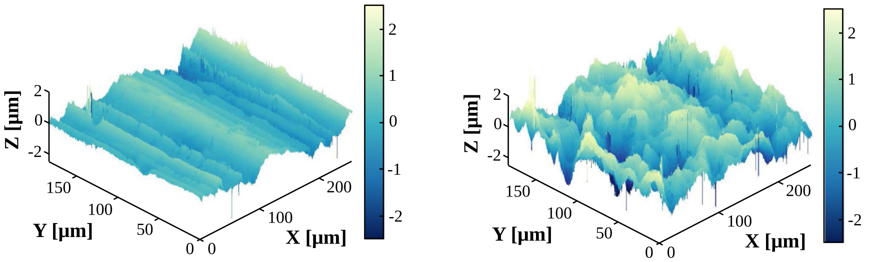
Several authors studied the influence of deformation on the adhesion between the polymer coating and the steel substrate. Boelen et al., 2004 and Van den Bosch et al., 2008 performed peel-off experiments and found that the bonding between the polymer and steel is reduced by (pre) deformation of the steel substrate. Laser-induced delamination experiments by Fedorov et al., 2007 showed a similar result. Recent results from Faber et al., 2014 revealed the presence of interface damage in DRD materials by exploring the interface in cross-sections using Focused Ion Beam milling. These papers suggest that the deformation-induced roughening of the interface is the cause of the loss of adhesion and possible delamination.

1.2. Challenges

It is well known that a polycrystalline metal, such as ECCS, roughens at its free surface when deformed, due to crystallographic differences between grains and other plasticity related phenomena. An example of the deformation-induced surface roughening for an ECC steel in tension is shown in Fig. 2. The initial height profile (Fig. 2(a)) reveals the presence of an initial rolling profile (grooves along the *y* direction, i.e. in the rolling direction (RD)). Tension was applied along the *x* direction (transverse direction (TD)). Upon deformation, the initial profile transforms to a new roughness profile during the tensile test (Fig. 2(b)). Clearly, this roughening occurs over a wide range of length scales, ranging from the scale of individual dislocations to the size of multiple grains. The resulting profile depends on the deformation conditions and the detailed material properties (Raabe et al., 2003).

The roughening phenomenon occurs at the polymer–steel interface during can production, which may result in interface damage. To predict the deformation and potential damage of these polymer-coated steels, an appropriate model has to be developed that incorporates the micro-scale phenomena governing the interface roughening.

In previous research, Van Tijum et al. (Van Tijum et al., 2007; Van Tijum et al., 2007) studied the influence of roughening on the interface properties by numerically generating a roughness profile. While these simulations give valuable insight into the influence of the out-of-plane displacements that can be expected during deformation of a polymer–steel interface, they do not include local in-plane deformations. Furthermore, the numerically generated surface profiles only resemble the average values of experimental measurements. Van den Bosch et al., 2008 also studied the effect of a change in interface roughness by including a roughness parameter, based on the Root-Mean-Square (RMS) roughness, in the adopted exponential



(a) Undeformed ECCS profile

(b) ECCS profile just before fracture occurs

Fig. 2. Initial and final surface profile of an ECC steel during a uniaxial tensile test, measured with a confocal optical profiler; X direction is the tensile direction; colors indicate the local surface height in microns.