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Preventing interface damage by pre-conditioning polymer-coated steels via rolling

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ABSTRACT

A novel methodology is presented for pre-conditioning a polymer-coated steel used in food and beverage packaging. Mechanical rejuvenation of the coating via rolling is studied in order to prevent interface damage in subsequent forming operations. The simulations reveal that the thermodynamic state of the polymer coating after rolling depends on the rolling reduction. This dependency can be used to tailor the thermodynamic state of the coating prior to can production. A proof-of-principle simulation was performed to study the effects of rejuvenation on subsequent deformation processes. Deformation-induced interface roughening was studied for the initial and rejuvenated polymer coating. The predictions for a rejuvenated polymer coating indicate a significant decrease in interface damage.

The presented numerical framework allows for a detailed study of the effects of pre-conditioning on the interface integrity during subsequent forming operations. With properly identified material parameters, it becomes possible to tailor the polymer–steel material properties before and during production to minimize interface damage during production and storage of cans or canisters, e.g. for food and beverage packaging.

1. Introduction

Recent years show an increase in the use of metal-polymer laminates in the form of electrolytic chromium coated steel (ECCS) sheets coated with a polymer layer (see Fig. 1) for packaging of food and beverages. Producing cans and canisters using pre-coated steel leads to a significant reduction of the environmental impact of the production process compared to conventional production methods. Traditionally, a can is first made from blank steel sheet after which several lacquering steps are necessary to apply a protective coating on the inside and a decorative coating on the outside. The reduction in environmental impact results from a reduction in energy consumption and CO_2 emission with one third and a reduction in process water and resulting solid wastes to practically zero (Van der Aa et al., 2000).

However, the pre-coated steel is subjected to several forming stages during production, i.e. deep (re-) drawing (DRD) and wall-ironing (see Fig. 2). These processes induce large deformations at high strain rates, pressures and temperatures. It has been shown experimentally that the interface accumulates damage during production and sterilization. While this damage is often not visible after production, it may become apparent during the prolonged product shelf-life. The food packaging industry demands that the polymer coating fully adheres to the ECCS substrate, even after a relatively long shelf-life, since this triggers corrosion and compromises the quality of the canned content (Boelen et al., 2004; Van den Bosch et al., 2008).

An example of the typical intrinsic response of glassy polymers under uniaxial compression is shown in Fig. 3. First, the polymer shows a nearly linear elastic response (1) after which the response becomes non-linear visco-elastic (2). After the yield point (3) is reached, depending on the thermodynamic state of the polymer (i.e. its age), softening is observed (4), which is overtaken by strain hardening at high strains (5). A key characteristic of polymer glasses is the fact that the yield point depends on the strain rate applied (Van Breemen et al., 2011).

The yield point thus depends on the thermodynamic state. The thermodynamic state refers to the (non-) equilibrium state of a

Abbreviations: ECCS, electrolytic chromium coated steel; DRD, Deep-draw, deep-ReDraw; PET, Polyethylene terephthalate; EGP, Eindhoven Glassy Polymer model [10]; RD, rolling direction; FE-DIC, Finite Element based Digital Image Correlation.

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glassy polymer, i.e. whether the polymer is close to or far away from its equilibrium state. When a polymer is cooled below its glass transition temperature (T_g), the mobility of the chains is decreased and the polymer moves away from equilibrium. However, the chain mobility is not zero and equilibrium will only be reached after an extended time, i.e. physical aging. The amount of softening seen in the mechanical response increases with physical aging. The process of moving the thermodynamic state of the polymer away from equilibrium, i.e. reverse aging, is called rejuvenation. Rejuvenation can be accomplished through a thermo-mechanical treatment (Klompen, 2005; Van Melick et al., 2003).

Recent results revealed the importance of the thermodynamic state of the polymer coating prior to deformation on the predicted interface damage (Van Beeck et al., 2015). A numerical–experimental study of the effect of deformation-induced interface roughening on the interface integrity of a polymer-coated steel indicated the existence of an optimum in the initial thermodynamic state of the PET (Polyethylene terephthalate) coating, i.e. the polymer age prior to deformation. A rejuvenated polymer shows (almost) no softening during mechanical deformation, while an aged polymer typically softens, see also Fig. 3. The simulations, which were performed using experimentally obtained full-field displacement fields of an evolving steel surface profile, predicted noticeably less interface damage for a rejuvenated coating compared to an aged coating. The changes in steel surface roughness trigger localization in the aged polymer coating, resulting in interface delamination. This localization behavior is significantly reduced for a rejuvenated coating, resulting in less damage.

After coating the steel substrate, the material is typically stored for extended periods of time. During this time, the coating ages continuously. Hence, rejuvenating the polymer coating towards the optimal initial thermodynamic state prior to production may decrease or even prevent the formation of interface damage.

It is well known that the thermodynamic state of a polymer can be tailored through a thermo-mechanical treatment (Van Melick et al., 2003). Thermal rejuvenation is accomplished by heating the polymer to a temperature above the glass transition temperature and then reducing the chain mobility via quenching. However, while a thermal treatment is relatively straightforward to apply in an industrial forming process, in the case of a polymer-coated steel it may lead to interface failure due to a mismatch in thermal expansion between the PET coating and steel substrate. Furthermore, the increased temperature required for rejuvenation may result in additional crystallization of the coating.

Another possibility is a mechanical rejuvenation procedure, e.g. rolling or ironing. The deformation imposed on the polymer-coated steel during such a procedure will induce stresses at the interface, i.e. normal and shear stresses, which may result in interface failure. However, a study by Van der Aa et al. (2000) showed that during wall-ironing of a polymer-coated steel the coating hardens due to the high pressure imposed on it. This hardening reduces the stress difference between the typically compliant polymer coating and the stiff steel substrate, since the post-yield response of the polymer depends on the hydrostatic pressure (Christiansen et al., 1971). However, wall-ironing induces large shear stresses in the material. Rolling may provide a more suitable mechanical rejuvenation method as the roll moves with the material to reduce the shear stresses. Similar to wall-ironing, a pressure is induced which is expected to reduce the stress mismatch further. Furthermore, the high pressure may delay or prevent crystallization of the PET coating (Zoller and Fakhreddine, 1994). Rolling the polymer-coated steel to tailor the thermodynamic state of the coating prior to production is thus an interesting pre-processing step to explore.

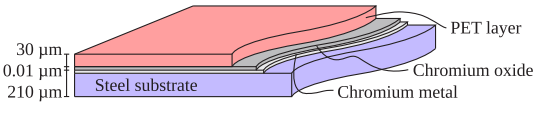

Fig. 1. Different material layers in a polymer coated ECC steel (after Van den Bosch et al. (2008)).

Several authors studied the effect of cold-rolling on the mechanical properties of polymers (Broutman and Patil, 1971; Matsuoka, 1998; Van Melick et al., 2003). Rolling of a coated material was investigated by Usov and Danilov (2007) by deriving the exact solution in case of an elastic coating and a rigid substrate material. A functionally graded elastic coating was recently studied by Guler and coworkers (Alinia et al., 2014; Guler et al., 2013). While these studies provide valuable insight into the mechanical behavior of a polymer during rolling, the behavior of a non-linear visco-elasto-plastic polymer coating on a steel substrate and the evolution of its thermodynamic state during rolling has not yet been investigated.

In this paper, the mechanical response of a metal-polymer bilayer material during rolling is investigated numerically using a non-linear visco-elasto-plastic material model for the PET coating. Furthermore, the change in the thermodynamic state is investigated as a means of pre-conditioning the material to prevent interface damage in subsequent deformation steps. Finally, the effect of the pre-conditioning on further deformation is studied in a proof-of-principle simulation of deformation-induced steel surface roughening.

The paper is organized as follows. The constitutive model and computational procedures for the rolling simulations are presented in Section 2. The simulation results are discussed in Section 3. The proof-of-principle simulations are presented in Section 4. The paper ends with a discussion in Section 5.

The following notations are adopted throughout the paper. A vector is denoted by $\vec{a}$ and a second-order tensor is denoted by $\mathbf{A}$. The inner product is defined as $\vec{a} \cdot \vec{b} = a_i b_i,\ i = 1,2,3$ and tensorial inner products as $\mathbf{A} \cdot \mathbf{B} = A_{ij}B_{jk}\vec{e}_i\vec{e}_k$ and $\mathbf{A} : \mathbf{B} = A_{ij}B_{ji}$. The transpose of a tensor is denoted by $\mathbf{A}^{\mathrm{T}}$ and the vector length is expressed as $||\vec{a}||$.

2. Constitutive and computational model

In this section, the material models for the polymer and steel are presented, along with their numerical implementation.

2.1. Polymer model

The studied coating consists of a PET layer with several additives to improve the PET–steel adhesion (Van den Bosch et al., 2008). PET is a glassy polymer and almost fully amorphous (crystallinity is approx. 8%). An example of the typical intrinsic behavior of amorphous glassy polymers under uniaxial compression is shown in Fig. 3. The intrinsic behavior of glassy polymers is thus complex and accurate modeling requires an advanced constitutive model.

In the past two decades, strong effort was put into accurately modeling the behavior of glassy polymers, e.g. the work of Boyce et al. (1988) and Govaert and co-workers (Van Breemen et al., 2011; Klompen et al., 2005). These models incorporate the non-linear visco-elastic behavior, as well as strain softening and hardening and the effects of temperature and time. Here, the so-called Eindhoven Glassy Polymer (EGP) model is adopted which adequately captures the complete intrinsic mechanical response of amorphous polymers (Van Breemen et al., 2011; Klompen et al., 2005). The EGP model is a multi-mode, multi-process constitutive model (Van Breemen et al., 2011). In the present work only one mode and one process is considered due to limited set of known PET