Interface and surface roughness of polymer-metal laminates
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Chapter 1

Introduction

1.1 The origin of food cans

The year was 1795. Napoleon put up a reward of 12000 Franks for a method of preserving food for his army having such long lines of provisioning that hunger began to tax its combat strength. Nicolas Appert, a French confectioner, won the prize in 1810. He placed sterilized food in glass jars, hermetically closed, secured by an iron wire and sealed with pitch. Because Nicolas Appert believed in hygiene and the use of the best fresh ingredients, he was able to make a small business out of it [1,2].

In the same year, Peter Durand received a patent from King George III for a tin-plated iron can as a food container. He was able to produce up to 60 cans a day. The invention in 1846 by Henry Evans of a device for making a can in a single operation lead to more widespread use of cans. Before these days cans were used only during long journeys and not always with the intended results. In 1845 during a search for the Northwest Passage around Canada, all 128 people under the leadership of John Franklin died. The deaths were the result of the lead solder that was used to seal the tin cans. The lead may have leaked into the food and driven the men to madness.

The most famous tin can is exhibited in the National Maritime Museum in London (Fig. 1.1) and was made by Appert. It is one of the first cans that took a journey even twice to the North Pole. This can was opened in 1938. The food was found to be nontoxic, at least for animals!

In 1966 the first cans are produced by the two-step "draw and wall ironing" (DWI) process and do no longer contain any tin. Millions of cans are produced every day, meeting criteria such as: environmentally safe, robust, a good storage capability, nice looking and also cheap to produce. Carbon steel does not meet these demands as it oxidizes. A coating may solve this problem and different kinds of coating were used, like metal and paint. None of them were very satisfactory until polymer coatings appeared. Polymer coated steels are able to fulfill the needs.

Nowadays, the production of polymer coated steel cans consists of the following steps. First, metal sheets are laminated with a polymer coating. This coating can be attached to the steel using direct extrusion or by heating the steel to attach the polymer sheets. After this, the laminate is quenched in order to keep the polymer coating amorphous. In a second step the steel is cut in circular disks called blanks. These blanks are shaped in several steps by deep-drawing. The outcome of the deformation process
Chapter 1

will have a cuplike shape with one side open. Eventually the can content is added and the can is sealed.

Fig. 1.1. A tin can from 1824, which was taken twice on a journey to the North Pole (taken from [3])

1.2 Scope of this thesis

This thesis concentrates on the mechanical performance of metal-polymer laminates, especially the impact of plastic deformation on the work of adhesion at the interface.

In general the metal and the polymer used in such laminates have very different mechanical properties; typically the metal has a much higher modulus, and a lower yield strain than the polymer. The mechanisms for plastic deformation in both materials are also entirely different. It is clear that during plastic deformation this mismatch in properties may lead to compatibility problems for the microscopic deformation near the interface. Plastic deformation of a laminate involves complicated structure evolution in both metal and polymer.

On the metal side the macroscopically imposed plastic strain induces dislocation movement on favorably oriented slip-systems within grains. Generally speaking this will lead to roughening of the interface as the dislocations escape the grains. In fact the roughening in itself is a rather complicated process, and in this thesis due attention will be given to this subject.

Since the polymer is much more compliant than the metal it is reasonable to assume that the roughening at the interface due to the deformation of the metal determines the deformation of the polymer near the interface, rather than the other way round.
At the same time the polymer, while it has to deform to the macroscopically applied strain, must also adapt to the displacements imposed to it by the metal at the interface. Fig. 1.2 shows a schematic representation of the situation. The cartoon shows the following interacting aspects: increase in surface roughness of the metal; a reduction of roughness at the free polymer surface; locally delamination of the polymer and the reduction of coating thickness. In the process of plastic deformation the evolution of the roughness is an important parameter.

The study of plastic deformation of polymer-metal laminates that is presented in this thesis specifically addresses the role of the evolution of roughness at the interface and its impact on the adhesion. So far aspects related to adhesion have been studied almost completely independently, e.g. adhesion [4], polymer deformation [5], surface roughness [4,6] and metal deformation [6]. A full analysis of the entire metal-polymer composite is still scarcely reported. The strength of this thesis will lie in the combination of all these aspects using various experimental and numerical techniques.

1.3 Measurement of adhesion

This thesis concentrates on the mechanical performance of metal-polymer laminates. Chapter 2 introduces the metal-polymer laminate that has been used throughout. This laminate is loaded uniaxially to simulate a crucial aspect of the forming process: the simultaneous roughening and stretching of the metal-polymer laminate. The interface roughness as a function of the applied strain is characterized by confocal microscopy.

In chapter 3 and 4, results of two experimental techniques are presented together with the numerical framework.

In the first experimental technique, the Laser Induced Delamination evaporates a thin layer of the coating and creates a pressurized blister [7] at the polymer-metal interface. For increasing laser power, the blister pressure increases and leads to delamination of adhering polymer around the blister. The resulting shape of the blister is characteristic for the work of adhesion.

The second experimental technique is the Asymmetric Double Cantilever Beam test [8]. In this technique, a support (glass) is attached at the polymer side of the laminate. A
Chapter 1

wedge is inserted between the metal and glass. By moving the wedge further between the metal and the glass, a crack develops on one of the two interfaces: metal-polymer or polymer-glass. The advantage of glass as a supporting medium is the possibility to follow the advancing crack as a function of time. These in-situ measurements are used to describe the crack statistics and mechanisms responsible for adhesive failure.

1.4 Effects of plastic deformation on the coating and the adhesion

Plastic deformation of the polymer-coated steel induces surface roughening of the metal. At the interface the polymer coating has to adapt to the displacements imposed by the metal and will deform. The deformations are partly elastic and partly plastic. The plastic deformation will be expressed in shear-bands. The deformation will increase the elastic stored energy in the coating and implicitly decrease the adhesive energy.

Chapter 5 reveals the implications of the metal roughening on the microscopic structure of the coating. Two experimental approaches are followed for the characterization of the behavior of the coating. As a first approach full-field birefringence microscopy is explored showing the deformation processes within the coating on a microscopic scale. Our second approach focuses on the surface morphology of the coating.

Numerical finite element simulations are used to interpret the experimental findings of the mechanical performance. One of the key features of the model is the ability to simulate roughening interface. Artificially generated interfaces are used to mimic the surface roughness evolution of the metal. This enables the simulation of all possible surfaces and therefore provides a tool to quantify the effects of surface roughness.

In the simulation the interface between the metal and the polymer is described by a mixed-mode (mode I and II) stress-separation law that defines the interface energy and an interaction length scale [9]. At the onset of deformation the surface of the substrate has a self-affine roughness characterized by the so-called Hurst exponent, a correlation length and an rms roughness amplitude that evolves with increasing strain.

Chapter 6 shows a numerical study that concentrates on the influence of the evolution of the interface roughness during plastic deformation of a metal, on the work of adhesion and on the interface energy with an amorphous polymer. The polymer coating is described with a constitutive law that mimics the behavior of PETG. It includes an elastic part, a yield stress, softening and hardening with increasing strains.

1.5 References

Introduction


