Progress in Organic Coatings 80 (2015) 156–163

Contents lists available at ScienceDirect

Progress in Organic Coatings

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

A forming limit curve for the corrosion resistance of coil-coatings based on electrochemical measurements

A.C. Bastos[a], G. Grundmeier[b], A.M.P. Simões[c,*]

[a] DEMaC and CICECO, University of Aveiro, 3810-193 Aveiro, Portugal
[b] Department of Technical and Macromolecular Chemistry, University of Paderborn, Warburger Str. 100, D-33098 Paderborn, Germany
[c] CQE and Department of Chemical Engineering, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form
30 September 2014
Accepted 25 November 2014
Available online 30 December 2014

Keywords:
Coil-coatings
Corrosion
EIS
FLC
Forming limit curve

ABSTRACT

Forming limit curves (FLCs) are useful tools to predict the safe forming limits of metal sheet. However, existing FLCs are limited to bare metal and the increasing use of pre-painted metal sheet (coil-coatings) requires new limits that take into account the corrosion resistance. In this work electrochemical impedance spectroscopy (EIS) was used to characterise the degradation of a coil-coated system in different states of deformation (uniaxial, biaxial and plane strain). The EIS data provided information about the condition of both paint and metal substrate and was used to devise criteria for minimum acceptable protection. A FLC was produced based on those criteria and its predictions were compared with the degradation of a model deep-drawn cup.

1. Introduction

Forming limit diagrams (FLDs) were initially developed by Keeler and Backhofen [1] and by Goodwin [2] in the 1960s. Until then the only reliable test of formability in metal sheet forming was the direct observation of whether or not the formed products were free of fracture and necking. FLDs became powerful tools providing an empirical gauge for forming limits. The key feature of a FLD is an experimentally determined forming limit curve (FLC), conventionally described as a curve in a plot of major strain vs minor strain – Fig. 1. The premise is that as long as the principal strains are significantly below this curve, the metal is safe from necking and tearing. Experimental methods for determining FLC are now well established [4–6].

The advent of pre-painted metal sheet (coil-coatings) brought a new problem to the field of limit prediction. In this material it is not just the metal sheet that is formed, but also the organic coating, as well as all other layers that may exist. Most commonly a coil-coating has a protective metallic layer (a thin layer of zinc or zinc alloys), pre-treatment (usually a brittle layer of phosphate) and various layers of paint (typically primer, mid-coat and top-coat). These layers have very different mechanical properties and respond differently to the same mechanical stress. It is difficult to predict the forming limits of a multilayer material like this. Moreover, the mechanical resistance is not the only matter of interest; corrosion resistance and aesthetics are also important, since this material is used as exterior cover of buildings and appliances.

In the present work a FLC was developed for the corrosion resistance of painted electrogalvanised steel. Samples of three different types of forming (uniaxial, biaxial and plane strain) were produced, with five degrees of deformation for each type. EIS was used to characterise the degradation of the paint layer and the corrosion of the metal substrate of each sample. Electrochemical parameters were used to estimate the limits of forming and, based on them, a FLC was constructed. The predictions given by the FLC were compared with EIS tests on model deep-drawn cups, which simulate real objects.

2. Experimental

2.1. Samples

The coil-coating used consisted of DC04 steel sheet 800 μm thick, with an electrodeposited zinc layer of 7 μm of nominal thickness and a phosphating pre-treatment. The paint scheme was composed by a 5 μm polyester primer plus a 15 μm polyurethane

* Corresponding author. Tel.: +351 218417963.
E-mail address: alda.simoes@tecnico.ulisboa.pt (A.M.P. Simões).

http://dx.doi.org/10.1016/j.porgcoat.2014.11.020
0300-9440/

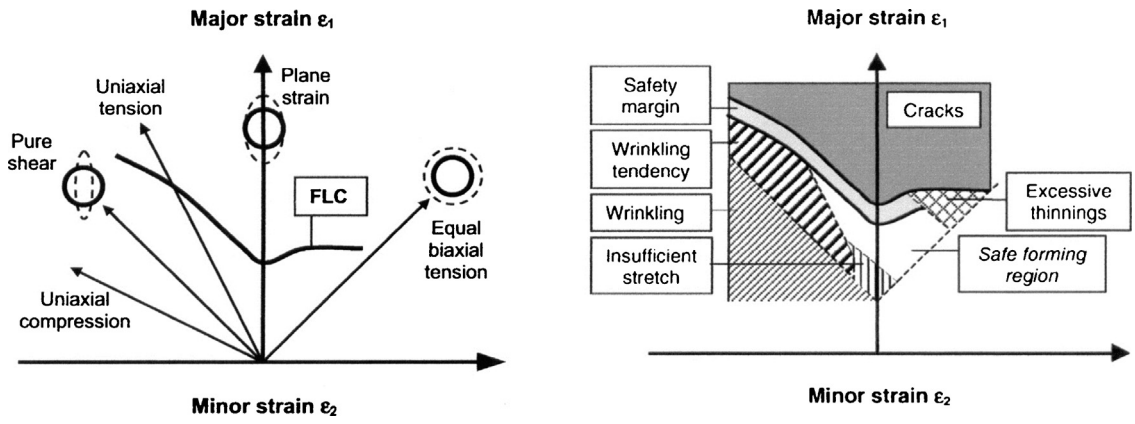

Fig. 1. Sketch of a forming limit curve, FLC and its corresponding forming limit diagram. Taken from Ref. [3] with permission.

mid-coat. To achieve faster degradation, no top-coat was used. Images of the different layers are shown in Fig. 2.

For the determination of the forming limit curve, samples with three types of mechanical deformation were produced – Fig. 3. Uniaxially strained samples (Fig. 3a) were produced by uniaxial traction. Plane strained (Fig. 3b) and biaxially strained (Fig. 3c) samples were produced by the Marciniak test. The strain was uniform in the flat top surface and only those regions were used for corrosion testing. For each type of deformation samples with five different levels of strain were produced. The major and minor logarithmic (or true) strains in each sample are presented in Table 1 and were determined by automated grid analysis with equipment and software from GOM mbH, Germany. A grid pattern of points was deposited on the surface of the unformed sheet and the deformation calculated by applying equation $\ln(l/l_0)$ in each principal direction, where l_0 and l are the distance between points before and after deformation, respectively.

Fig. 3d shows the model sample produced by deep drawing with the objective of testing the FLD. The strain distribution in this sample was also determined by automated grid analysis and is presented in Fig. 4.

2.2. Electrochemical impedance spectroscopy

Measurements were made on the flat area of the samples by exposing them to aqueous 5% (0.86 M) NaCl. A three-electrode arrangement was used, with a saturated calomel electrode as reference, a platinum counter electrode and the exposed sample area acting as working electrode. The cells were connected to Gamry (FAS1 Femtostat coupled to a PC4 controller board) or Solartron (1286 Electrochemical interface and HF 1255 frequency response analyser) instrumentation. All measurements were performed at room temperature, in a Faraday cage, with the solution quiescent and exposed to air. Impedance measurements were made at open

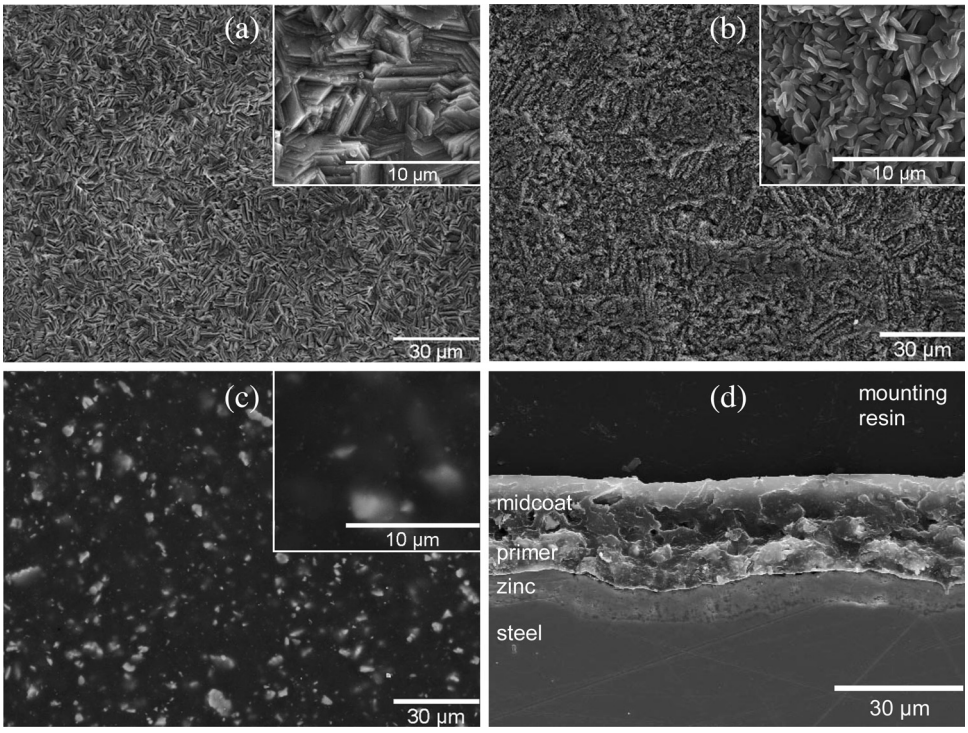

Fig. 2. Microscopic aspect of the different layers of the coil-coating: (a) electrogalvanised layer, (b) phosphate layer, (c) paint layer and (d) cross-section of the layered system.