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A combined experimental-numerical investigation of the failure mode of thin metal foils

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Abstract

A combined experimental and numerical analysis of the mechanical response of the thin aluminum foils employed in beverage packaging has been performed using 3D digital image correlation and non-linear finite element techniques. The present contribution focuses on the significant amount of out-of-plane displacements that develop in tensile tests as fracture propagates across the investigated specimens. The influence of this phenomenon on the actual failure mode of the considered metal samples is further discussed.

Keywords: pipeline steel; material aging; mechanical characteristics; indentation

1. Introduction

Thin metal foils are employed in several technological fields related to the production of micro-devices, flexible electronics and beverage packaging (Read and Volinski, 2007; Wong and Salleo, 2009; Bolzon et al., 2015). In these applications, the metal thickness is of the order of a few microns or even less. The foil properties are influenced by the lamination processes and differ from those of the corresponding bulk materials. In particular, the apparent material brittleness increases as the thickness is reduced. At the same time, thin samples are difficult to handle and their mechanical response is sensitive to local imperfections, size and geometric effects (Klein et al., 2001; Hu, 2003; Wang et al., 2003). Thus, for instance, the overall load versus displacement output recorded during uniaxial

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tensile tests may not be directly correlated with the local stress-strain response.

The interpretation of the results can be enhanced by full-field monitoring techniques complemented by simulation models of the experiment (Avril et al., 2008; Bolzon, 2014). This approach has been applied to the case of thin aluminum foils employed in beverage packaging.

A three-dimensional digital image correlation (3D-DIC) technique has been exploited to measure the displacement distribution and the configuration changes of non-conventional metal samples subjected to tensile load. The performed measurements evidence the significant amount of out-of-plane displacements that develop as fracture propagates across the investigated specimens. The influence of this phenomenon on the actual failure mode of the considered metal samples is discussed in this contribution with the aid of non-linear finite element models of the experiment validated in former investigations (Bolzon et al., 2015).

2. Experimental investigation

Tensile tests have been performed on notched specimens cut from thin aluminum foils (9 μm nominal thickness). The considered material configurations are shown in Fig. 1. The sample dimensions are approximately 250 mm length and 100 mm width, comparable with those considered in former investigations (Andreasson et al., 2014). The deformation of the specimens and the crack propagation has been followed by a 3D-DIC technique.

The resolution achievable with 3D-DIC permits to detect phenomena like material separation and crack propagation at early stage, well in advance with respect to visual inspection (Mathieu et al., 2012). The measurement accuracy of DIC depends on the experimental conditions (Zappa et al., 2014): it can be optimized by the specimen preparation and by image pre-processing (Mazzoleni et al., 2015).

In the considered experimental set-up, a stereo camera system mounted on a tripod points the specimen, which is connected with the loading machine by clamps. Two LED-based lighting devices are mounted nearby. The light intensity and projection angle with respect to the metal sample are tuned in order to avoid specular reflection and to get the optimal quality of the image observed in a monitor. An external trigger is used to synchronize the two cameras. The image acquisition frequency is 1Hz.

The stereoscopic vision system allows to detect the spatial deformation of the foil under the increasing applied load. The dimensions of the field of view are set to 220x160 mm in order to acquire images of the full area of the specimen. A pair of GX3300 cameras equipped with 50 mm focal length optics (Zeiss Makro Planar T 2/50) are used to acquire the images for DIC. The full resolution thus achieved is 3296×2472 pixels (px), with about 15px/mm in the camera field of view.

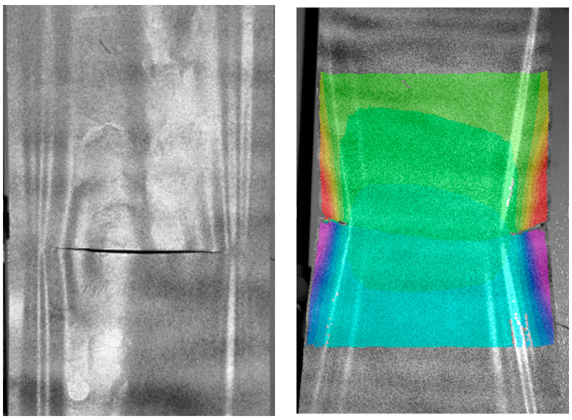

Fig. 1. Snapshots of the notched material specimens subjected to tensile test and DIC reconstruction of the displacement distribution in the loading direction (vertical in the images).

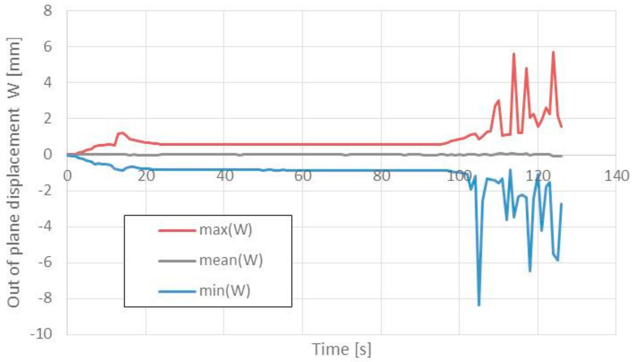

Fig. 2. Maximum and minimum out-of-plane displacement during the test.

The surface of the specimen is prepared with a random speckle obtained with black spray paint. The accuracy of the DIC measurement is strongly related to the characteristics of the speckle generated on the monitored surface; the optimal size of the speckle is around 4-5px on average, corresponding in this application to approximately 0.3mm. The contrast of the speckles with the background is increased and the negative effect of the reflection light is reduced by painting the specimen surface white first. The speckle is then generated by means of an airbrush, changing the nozzle and the air pressure to control the size of the black paint particles and to obtain their optimal average size.

The full-field deformation of the investigated material samples is recovered during the test. The extreme values of the out-of-plane displacements measured in the case of a plain metal foil are reported in the graph of Fig. 2. Notably, the amplitudes are magnified in the last (softening) phase of the experiment, during material separation.

3. Numerical analysis

The tensile tests performed on the thin aluminum foils considered in the present investigation have been reproduced in a finite element context (Abaqus, 2015), considering both material and geometric non-linearity. The classical elastic-plastic constitutive law based on Hencky-Huber-von Mises criterion with isotropic hardening rule represents the constitutive metal response in the numerical model. Material parameters coincide with those employed in former investigations (Andreasson et al., 2014; Bolzon et al., 2015). The simulations evidence that a significant compressive state arises orthogonally to the loading direction and in the proximity of the notches, as shown for instance by the contour plots drawn in Fig. 3.

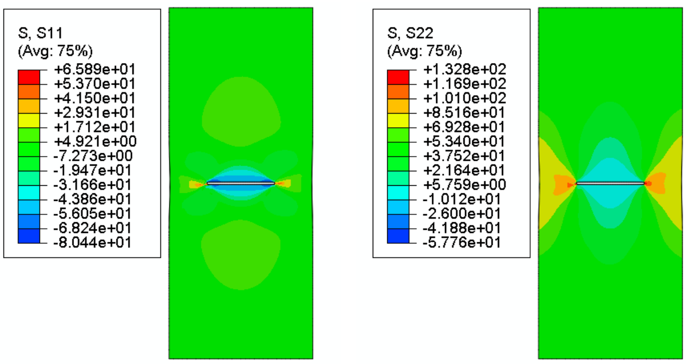

Fig. 3. Distribution of the stress components arising from the uniaxial tensile test, acting orthogonally (S11, left) and in parallel (S22, right) to the loading direction (vertical in the graphs).

4. Discussion

The full-field monitoring of the performed tensile tests detects a significant amount of displacements developing in the direction orthogonal to the specimen surface. The observed deformation is a likely consequence of the geometric instability induced by the compressive stresses evidenced by the numerical simulation. The out-of-plane deformation (warping) is enhanced in the crack propagation phase. Thus, different interacting non-linear phenomena influence the overall response of the sample, that can be fully captured only in a three-dimensional modelling space.

The analyses performed so far rest on the elastic-plastic idealization of the metal response. This assumption is motivated by former studies (Bolzon et al., 2014; Bolzon and Shahmardani, 2017), which suggest that failure of thin free-standing aluminum foils and laminates is mainly induced by strain localization and necking. The possibility of introducing displacement discontinuities in order to account for material separation explicitly represents a still open issue, also due to the uncertainties associated to the definition of a specific traction-separation law (Tallinen and Mahadevan, 2011; Pfaff et al., 2014).

5. Closing remarks

The in-plane deformation of the thin aluminum foils subjected to the tensile tests considered in this investigation is accompanied by warping, already documented by Kao-Walter (2004). Numerical simulations permit to understand the origin of this phenomenon. The computational results gathered so far present a fair qualitative agreement with the experimental observations, while quantitative matching requires additional efforts. Further analyses shall also consider the influence of imperfections on the load-displacement output usually exploited to material characterization purposes.

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