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Numerical modeling of the Disk Pressure Test up to failure under gaseous hydrogen

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ABSTRACT

The present work focuses on non-linear finite element simulations of the Disk Pressure Test, used for characterization of hydrogen embrittlement of metallic materials by bulging out a thin disk under gas pressure until failure. The modeling is based on both elastoplastic and diffusion computations at the macroscopic scale. Hydrogen sensitive cohesive elements are used for crack propagation. Comparison of numerical predictions with experimental data on steel and Inconel gives good agreement both on macroscopic displacement–load curves and on global hydrogen embrittlement features.

1. Introduction

Metallic sheets are widely used for storage and transportation of gaseous hydrogen (as pipes, pressure cylinders), which needs reliable structure optimization and safety predictions accounting for hydrogen embrittlement. In this context, finite element simulations of real processes involve several non-linear coupled phenomena, namely metal–hydrogen interactions, material behavior and hydrogen-induced fracture.

The aim of the present study is to develop such simulations from a purely phenomenological approach in the case of the Disk Pressure Test. This experiment (hereafter named DPT) is used to define the hydrogen-sensibility of materials as extensively explained by Fidelle (1988), and has been chosen for technical standardization purpose by French Standard (1990) and ISO normalization (2005).

In the DPT (see Fig. 1), a thin disk is bulged out until fracture by applying gas pressure on its lower face. The ratio of the ultimate pressures obtained with a neutral gas (e.g., helium) and with hydrogen defines a phenomenological index for material hydrogen sensitivity. The fatal crack initiates generally near the holding device, in the zoomed area of Figs. 1 and 2.

The DPT is partly similar to hydraulic bulge tests used in sheet metal forming, mainly to obtain forming limit curves and material behavior identification under biaxial large plastic strain, as described in Banabic et al. (2000). However, in the DTP, the disk diameter is lower than in the usual bulge test, leading to expected higher influence of the boundary conditions in the stress gradients through the sample. Finite element simulations of bulge tests are available in literature. Ahmed and Hashmi (1998) have studied the influence of various loading conditions on the deformed shape. More recently, Alsos et al. (2008) have used bulge tests to apply a criterion for plastic instability. Saanouni (2008) performed finite element simulations up to complete blank failure including crack propagation thanks to remeshing techniques. Only few works, nevertheless, have focused on the particular configuration of the Disk Pressure Test, and are performed without any treatment either for fracture or for hydrogen effect: Beghini et al. (1996) on high chromium martensitic steels, and Bouajila (2008) on copper alloys, used simulations mainly to get the stress and strain level in the disk just prior experimental failure.

On the other hand, fracture is commonly modeled using cohesive elements, and different traction-separation laws (TSL) have been proposed, depending on the problem, as reviewed by Chandra et al. (2002). The influence of hydrogen on failure has been studied through different approaches in order to provide a physically based correlation between the TSL and the local hydrogen concentration. Serebrinsky et al. (2004) have based their formulation on atomic level interactions, while Liang and Sofronis (2003) used thermodynamical considerations. More generally, hydrogen influence on TSL is accounted for through phenomenological considerations. finite element is then mainly used to model crack propagation in notched samples submitted to tensile tests, which are generally far from real loading conditions in a technological context.

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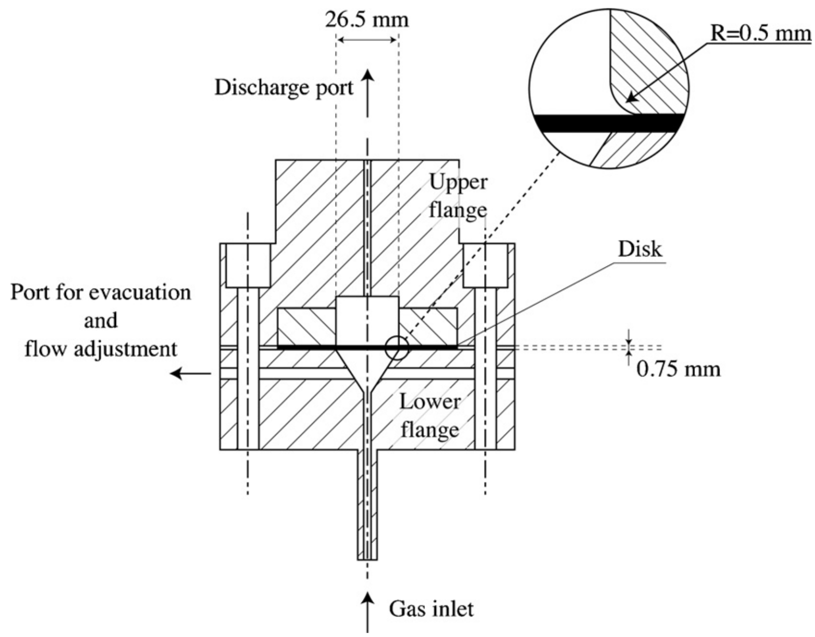

Fig. 1. Principle of the DPT (from ISO normalization, 2005) and disk before testing (in black). The enlarged view shows the zone of interest for fracture.

In the present work, finite element simulation of the DPT is developed to predict failure pressure under hydrogen, for different materials and thickness, in order to analyze the response for a large range of pressure conditions, extending outside the standard conditions, especially useful for high pressure hydrogen storage.

Hydrogen dependent cohesive elements are used to promote crack initiation and propagation in the potential failure zone of the disk. Hydrogen embrittlement is then assumed to induce sudden cracking in a fully plastically deformed sample. As a first step, only simple global models are considered for material behavior and diffusion process.

Hypotheses of the model and numerical assumptions are first presented, then the finite element simulations are applied to experimental DPT obtained on two different materials of industrial interest. The model ability to predict conditions of disk failure under hydrogen pressure is discussed.

2. Disk Pressure Test modeling

The numerical simulation of the DPT was conducted with Abaqus© software assuming the axisymetry of the problem. For all the applications considered in the present work, the embrittlement process under hydrogen gas led to a brittle-like failure of the disk near the holding device.

2.1. Finite element modeling

The general geometry of the Disk Pressure Test is presented in Fig. 2. The sample was meshed using the bilinear quadrangular element with four nodes and 4 integration points called CAX4T from ABAQUS element library, used for the resolution of the coupled mechanical-diffusion problem. The size of finite elements was set to 20 μm in the whole disk. It was checked that such a size led to

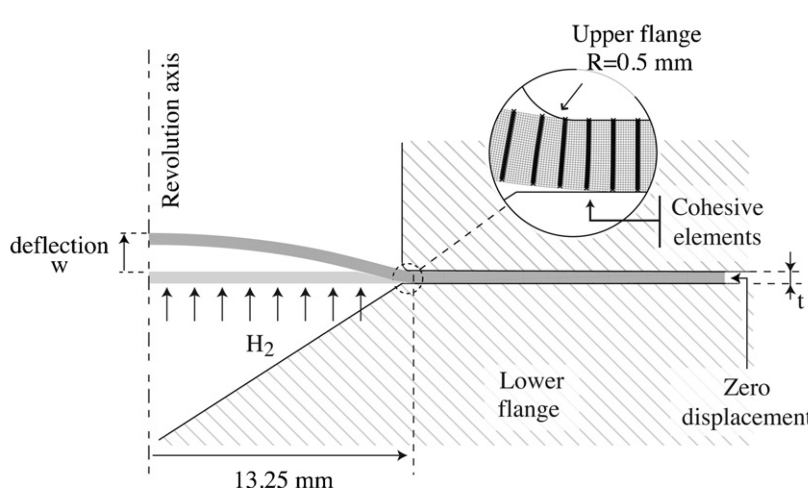

Fig. 2. Modeling of the disk pressure test: configuration, boundary conditions, and mesh, including six cohesive element lines in the potential failure zone (t = 0.6 mm, element size 20 μm).