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Dynamic Fracture of Ductile Materials

Dynamic fracture behavior of high strength pipeline steel

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Abstract

The occurrence of a crack propagating along a pipeline is a catastrophic event, which involves both economic losses and environmental damage. Therefore, the study of the fracture initiation and propagation properties of a pipeline is an essential part of its integrity assessment. Fracture prediction, however, is a challenging task, since it requires knowledge of the interaction between the dynamic forces driving crack growth, and the resistance forces opposing fracture propagation. Moreover, plenty of material properties should be taken into account. Aiming at a better understanding of the plastic hardening, damage and fracture properties of an API 5L X70 pipeline steel, and how these are affected by the strain rate, in present contribution, a comprehensive set of test results is presented. The program includes static and dynamic tensile tests on smooth and notched samples, and compression tests on cylindrical samples. Test result analysis is supported by finite element (FE) modelling. As such, the study aims at providing data needed for both fundamental material research and constitutive material modelling.

Peer-review under responsibility of the scientific committee of the International Conference on Dynamic Fracture of Ductile Materials

Keywords: Fracture propagation; plastic hardening; damage; strain rate; finite element; constitutive modelling

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1. Introduction

Steels utilized for the construction of oil and gas pipelines have to exhibit exceptional material properties to cope with severe working conditions. From a mechanical perspective, these conditions involve high internal pressures in the pipe, environmental temperatures far below the freezing point and high bending loads during offshore pipe laying. Legislative authorities obligate the suppliers and operators of the pipelines to meet high standards for environmental protection and safety by ensuring material and structural properties that conform to globally acceptable standards. One of these standards is the ISO 3183 of the International Organization for Standardization, defining steel grades including minimum values for strength and toughness, giving structural requirements like minimum wall thickness and setting the manufacturing requirements like the quality of the weld seams.

The occurrence of longitudinal cracks along gas pipelines has made it essential to have fracture propagation control to ensure pipeline integrity. Toughness tests such as Charpy tests and Battelle drop weight tests complemented by numerical simulation of ductile crack propagation and arrest are used to yield a conservative prediction of the fracture control strategy [1, 2]. The constitutive behavior of pipeline steels is often modelled taking into account quasi static conditions. However, Charpy and Battelle tests are dynamic events which require the knowledge of the strain rate sensitivity of the pipeline material. Additionally, very high strain rates can occur in the vicinity of a running crack in a high pressure gas pipeline. As such, the constitutive model has to account for strain rate sensitivity. The dependence of the fracture behavior on the strain rate of a commercial pipeline steel was extensively studied by S. de Luna et.al [3] wherein the material fracture toughness was found to increase slightly with strain rate. The analysis was also supported by micromechanical damage model. The important effect of the dynamic loading rates on the material resistance and on the tensile and initial toughness properties of steels was identified by C.S Wiesner et.al [4]. Increasing loading rates was observed to cause a shift from ductile fracture behavior at low rates to brittle behavior at high rates of loading and a method to predict this transition zone was also proposed. Moreover, a strain rate dependent cohesive zone finite element model has been developed to analyze the speed dependent fracture behavior of pipeline steels as observed in drop weight tear tests and to understand the dependence of the fracture toughness on crack speed which is critical for material selection and crack arrest design in high strength steel pipelines [5].The results suggested that strain rate effect in the bulk material could be largely responsible for the speed dependent dynamic fracture and model could be used to effectively predict the behavior. However, it has to be supplemented with sufficient experimental data in the dynamic ranges. Hence, it is imperative to have high strain rate tests for dynamic characterization of pipeline steels.

Conformance of the product with the applicable standards are ensured by performing a series of material and mechanical tests covering the entire range from small scale tensile tests to full scale burst tests under realistic conditions of use. Present study reports on an extensive experimental program that has been devised to characterize the plasticity, damage and fracture properties of an API 5L X70 pipeline steel. The program includes static and dynamic tensile tests on smooth and notched samples, and compression tests on cylindrical samples. Result analysis and interpretation is supported by finite element simulations of the tests.

2. Material and techniques

2.1. Test material

The material studied is an API 5L X70 pipeline steel provided by ArcelorMittal as hot rolled coil with a thickness of 14.8mm. The microstructure consists of a ferritic matrix with a low pearlitic content of 3%. All the samples are extracted in the rolling direction by mechanical machining.

2.2 Static testing

For the low strain rate experiments, an Instron material testing machine (Model 5569) is used. To ensure the same boundary conditions as in the dynamic tests, the samples are fixed between two slender loading bars in the same way as in the dynamic tests, see Fig. 1. Tests are performed at three different crosshead velocities, aiming at strain rates of 0.00025, 0.0025 and 0.025 s^{-1} in the central gauge or notch section of the samples. The lowest strain rate is selected in accordance with ISO 6892:1. Since the crosshead displacement systematically overestimates the actual sample