International Journal of Impact Engineering 88 (2016) 153–171

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Low-velocity impact on high-strength steel sheets: An experimental and numerical study

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ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 29 September 2015
Accepted 2 October 2015
Available online 10 October 2015

Keywords:
Sheet-impact
Advanced high-strength steel
Necking
Failure

ABSTRACT

Low-velocity impact tests were performed on dual-phase and martensitic steel sheets and compared with corresponding quasi-static tests. The geometry and loading condition of the specimens were similar to formability tests, and the average strain rates before failure were in the range 80–210 s^{-1} for the low-velocity tests and 0.002-0.005 s^{-1} for the quasi-static tests. For both loading rates, the sheets failed under pre-dominant membrane loading, and by varying the specimen geometry, the stress states prior to failure ranged from uniaxial tension to equi-biaxial tension. Thus, the most important stress states occurring during an impact event in a thin-walled structure are covered. The experiments were complemented by nonlinear finite element simulations, where higher-order solid elements and a refined mesh were applied to capture the failure of the sheets. The materials were modelled using the Hershey high-exponent yield function combined with the associated flow rule and isotropic hardening. Quasi-static tensile and shear tests and tensile tests at elevated strain rates were performed to calibrate the constitutive relation. The results in terms of force-displacement curves and strain histories at critical positions in the specimens were similar for low-velocity and quasi-static loading, independent of material and specimen geometry. This indicates that the quasi-static test gives a good description of the sheet behaviour under low-velocity impact loading. The numerical simulations were found to be in good agreement with the experimental results, and strengthened the experimental finding that all the sheet-impact tests, except the martensitic steel sheet in a state close to equi-biaxial tension, displayed local necking before final fracture.

1. Introduction

The low-velocity sheet-impact problem is of interest in many engineering applications, such as protection against dropped objects in the design of offshore structures [1], design against grounding [2] and ship–ship collisions [3] in ship building, and prediction of the onset of necking in the metal forming industry [4].

In most of the low-velocity sheet-impact studies reported in the literature, the parameters investigated have been the nose shape, the mass or the impact velocity of the impactor, the position of impact on the target, the boundary conditions of the sheet, or the sheet material, e.g. Refs. 5–8. Common to these studies is that failure occurs locally at the nose of the impactor and the failure mode is typically plugging in the case of a blunt nose and petaling in the case of an ogival nose. Other failure modes, which may occur in sheets exposed to membrane stretching, are local necking and through-thickness shear fracture. However, these failure modes have mainly been studied in the quasi-static regime.

Alsos and Amdahl [9] studied the indentation resistance of stiffened and unstiffened panels exposed to quasi-static loading. Simulations with a local instability criterion and large shell elements [10] were able to give a reasonable prediction of failure. Simonsen and Lauridsen [11] presented experimental results on 1 mm steel sheets exposed to quasi-static loading by semi-spherical impactors with various diameters. The sheets were fixed with square, rectangular or circular boundaries, and failed by local necking followed by material fracture. A detailed study on the failure modes in Nakajima formability tests on 1.5 mm thick steel sheets was conducted by Björklund and Nilsson [12]. Local necking occurred before fracture in all the tests, except for those experiencing stress states close to equi-biaxial tension. Hogström et al. [13] observed necking before fracture in formability tests on 4 mm thick mild-steel sheets for stress-states ranging from uniaxial tension to equi-biaxial tension. Usually formability tests on steel sheets exhibit failure by necking rather than fracture, an exception being equi-biaxial tension where

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http://dx.doi.org/10.1016/j.ijimpeng.2015.10.001
0734-743X/

Table 1
Chemical compositions of the materials (in weight %) [17,18].

Material	C	Si	Mn	P	S	Al_{tot}
600DL	0.10	0.40	1.50	0.010	0.002	0.040
1400M	0.17	0.20	1.40	0.010	0.002	0.040

the failure mode depends on the material. Stören and Rice [14] proposed a model to predict material instability based on the assumption that this phenomenon appears simultaneously as the initiation of a vertex on the yield surface. This model predicted well failure in several equi-biaxial tension tests reported in literature. An extension of this model introduced by Jie et al. [15], taking into account the strain-rate effect, improved considerably the prediction of failure in formability tests on steel sheets with strain rates around 0.4 s^{-1}.

In formability testing, the experimentalist has control of the stress state in the material before failure. However, this type of tests is usually restricted to quasi-static loading conditions. An exception is the study of Walters [16] who performed dynamic Hasek tests on DP780 steel sheets in a drop tower. The tests were carried out to investigate the effect of stress state and strain-rate on the material's ductility. It was found that the influence of strain-rate on the ductility depended on the stress state.

In this study, two experimental programmes were carried out for thin sheets made of either dual-phase steel or martensitic steel. The main experimental programme involved a novel set-up for low-velocity and quasi-static punch tests on sheet metals. The test set-up was designed to obtain sheet failure under membrane loading and to cover stress states within the range of traditional formability tests. This way the most dominant stress states occurring during an impact event are covered. The second experimental programme consisted of material tests, namely quasi-static and dynamic tension tests and quasi-static shear tests. The sheet-impact tests were studied experimentally and numerically, using the results from the material tests to calibrate constitutive models for the materials. It was found that the low-velocity and quasi-static sheet-impact tests exhibited similar response, which implies that the quasi-static tests give a good indication of the sheet behaviour during low-velocity impact. Further it was found that all tests failed by local necking, except for the martensitic steel sheet in a state close to equi-biaxial tension which failed by through-thickness shear fracture induced by shear-banding.

2. Materials

Two high-strength steel sheet materials, Docol 600DL and Docol 1400M, were provided from Swedish Steel AB (SSAB). The sheet thickness was 1.8 mm for Docol 600DL and 1.0 mm for Docol 1400M. Docol 600DL is a dual-phase steel with low yield strength and high work hardening. The nominal yield and ultimate stresses are reported from the manufacturer to be in the range from 280 MPa to 360 MPa and from 600 MPa to 700 MPa, respectively [17]. Through heat treatment the material is given a two-phase structure of ferrite and martensite. The ferrite gives good formability, while the martensite provides the strength. Docol 1400M is a cold-reduced and fully martensitic steel with high strength. The manufacturer reports a minimum yield strength of 1150 MPa and nominal ultimate strength between 1400 MPa and 1600 MPa [18]. The high strength is produced by very fast water quenching from an elevated austenitic temperature range. The chemical compositions of the materials are given in Table 1.

To form the basis for constitutive modelling of the materials, a set of material tests was carried out. Uniaxial tension tests were used to provide true stress versus plastic strain curves up to necking and

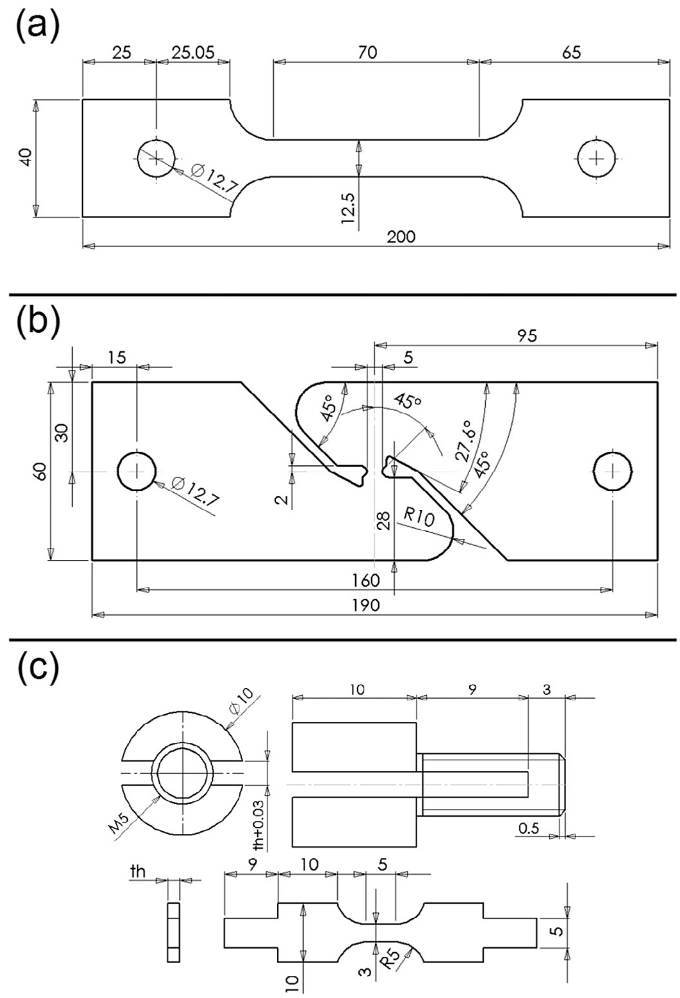

Fig. 1. Geometries of material test specimens: (a) uniaxial tension, (b) in-plane shear and (c) uniaxial tension in split-Hopkinson tension bar.

to investigate if the materials display significant plastic anisotropy. Shear tests were used to find the stress–strain behaviour for large strains and to determine the shape of the yield surface. The rate dependence of the materials was determined from split-Hopkinson tension bar tests.

2.1. *Uniaxial tension tests*

Uniaxial tension tests were carried out under displacement control in a Zwick/Roll hydraulic testing machine with a capacity of 30 kN. The nominal geometries of the specimens are given in Fig. 1(a). The loading rate was 4 mm/min giving a strain rate before necking of $\dot{e}_0 = 1.0 \cdot 10^{-3}$ s^{-1}. For both materials, specimens were cut out at 0°, 45° and 90° to the rolling direction in order to investigate in-plane anisotropy. Two successful tests in each loading direction are presented, thus giving a total of 12 tests for the two materials.

To acquire local strain data from the tests, digital image correlation analyses were performed. Before testing, one side of the specimen was spray-painted with a combination of black and white paint, obtaining a high-contrast speckle pattern to improve the optical measurements. The tests were recorded by a Prosilica GC2450 digital camera equipped with 50 mm Nikon lenses at a frequency of 2 Hz. The images were post-processed using an in-house digital