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Mechanical behaviour of dual-phase high-strength steel under high strain rate tensile loading

Jingui Qin, Rong Chen, Xuejun Wen, Yuliang Lin, Minzu Liang, Fangyun Lu*

College of Science, National University of Defense Technology, 410073 Changsha, P. R. China

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ABSTRACT

The effects of strain rate on the tensile properties of two commercial steels (DP700 and DP500) were investigated. Quasi-static tests (0.001 s^{-1}) were performed using an electromechanical universal testing machine, whereas a split Hopkinson tensile bar apparatus was used for testing at high strain rates (~1100 s^{-1}, ~1800 s^{-1}, and ~3200 s^{-1}). The two high-strength steels show significant strain rate sensitivity. The material parameters of the existing Johnson–Cook model were determined from experimental results. This model fits the experimental data well in the plastic zone. Digital image correlation was used together with high-speed photography to study the strain localisation in the tensile specimens at high strain rates. By using digital image correlation, the in-plane strain field and local fracture strain of the specimen were obtained. The contours of the strain field indicate an early localisation even before the peak load is attained. Numerical simulations of the dynamic tensile tests were performed using the non-linear explicit finite element code LS-DYNA with the Johnson–Cook model. Good correlation between the experiments and numerical predictions is achieved, in terms of the strain gauge signals, deformed geometry, and strain field.

1. Introduction

An important challenge in the automotive industry is the design of light-weight and safe auto-body structures with enhanced crash response. This objective leads to the increasing use of high-strength steel sheets for auto-body members. To fulfil the new structural performance needs in the automotive industry while minimising the impact on structural mass, a new generation of advanced high-strength steel (AHSS) has been developed. Members of the AHSS family include the dual phase (DP), transformation-induced plasticity, complex phase, and martensitic steels. The DP-type steels are low-carbon steels with soft ferrite and hard martensite. DP steels are annealed by holding the strip in the $\alpha+\gamma$ temperature region for a set period of time and then quenched so that the austenite is transformed into martensite and the ferrite remains on cooling. The amount of martensite in the steel can be controlled to determine the strength level ranging from 350 to 1000 MPa [1]. Many researches [1–4] have been carried out for DP steels that satisfy the high strength as well as the high formability. The mechanical behaviour of materials at high strain rates is considerably different from that observed at quasi-static loading because of the strain rate sensitivity of the material. The determination of the material properties at high strain rates is a key step towards the effective design of automobile components and the accurate modelling of vehicle crash tests.

The most widely used method for high strain rate testing in the range of strain rates from 10^2 s^{-1} to 10^4 s^{-1} is the Split Hopkinson bar method [5] due to its relative simplicity and robustness. Several authors have reported the dynamic tensile test on AHSS using the split Hopkinson tensile bar (SHTB) technique, the effects of the strain rate on the tensile strength, elongation at fracture, and the absorbed energy were examined in most of the literature [2,6–10], and the results of SHTB test have been used to design structural applications of steel and to extract the constitutive model parameters used in numerical simulation. However, a homogeneous stress and strain distribution is assumed in the gauge section of the specimen. Thus, SHTB testing can only provide the average stress and strain in the gauge section of the specimen. When come to extract the local material behaviour from the global specimen response, a new technique is needed.

A robust approach to obtain more accurately the local strain in a specimen is to use optical strain measurements, such as the Moiré phase shifting and digital image correlation (DIC). Verleysen et al. [11,12] performed a combined optical-numerical technique to measure the axial displacement (strain) at all points along the axis of the specimen during the SHTB experiment, the result displayed local strain clearly. However, the information of the strain distribution

* Corresponding author. Tel.: +86 73184573276; fax: +86 73184573297.
E-mail addresses: jgqin@nudt.edu.cn (J. Qin), R_Chen@nudt.edu.cn (R. Chen), wenxuej@nudt.edu.cn (X. Wen), ansen_liang@163.com (Y. Lin), mzliang@nudt.edu.cn (M. Liang), fangyun_lu@163.com (F. Lu).

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along the transverse direction of the specimen could not be obtained because their method only monitored the displacement of the line grid that was attached to the specimen and was perpendicular to the loading axis. That is, the strain distribution obtained from their method is one-dimensional. The DIC technique could determine the in-plane strain distribution of a specimen by detecting the trace of the fine speckle attached to the specimen. As a two-dimensional full-field measurement, DIC has become popular in problems related to solid mechanics [3,13]. Some useful local information, which might be difficult to measure using other methods, can be obtained using DIC. For example, the fracture strain is usually used as a criterion for deleting an element during finite element (FE) simulation. DIC can extract this parameter by comparing the nearly fractured image to the reference one.

Numerical simulation based on the FE is a proven method to calculate the stress and strain distribution in test specimens. In this way, a better insight into the material local response of the specimen is acquired. The validity of simulation is highly dependent on the expression and parameters of the material model, as implemented in the FE model. Numerous constitutive models have been used to describe the mechanical behaviour of steel, such as the Cowper–Symonds model [6], Johnson–Cook model [6,8,14–19], Voce law [15], Zhao model [8,16], and extended Ludwig model [16].

In this paper, the mechanical behaviour of two types of commercial steels: DP700 and DP500, have been investigated under uni-axial tensile loadings. The tensile stress–strain responses under quasi-static (QS) conditions of 0.001 s^{-1} and high strain rates of ~1100, ~1800, and ~3200 s^{-1} are presented. Elevated strain rate testing was performed using a SHTB apparatus. Stress–strain curves were then analysed to assess the effects of strain rate on the performance of the investigated steels. Both QS and dynamic test results were subsequently used to model the strain rate and temperature dependent constitutive behaviour of the materials. For this purpose, a widely used the phenomenological Johnson–Cook model [20], which is implemented in most commercial finite element codes, is used. The experimental data were fit to the Johnson–Cook constitutive model and model predictions were compared with the measured data. The DIC technique combining high-speed photography was used to obtain the strain distribution of the specimen during the dynamic loading of a representative test. The local deformation of the full-field specimen was clearly displayed and the fracture strain (local parameter) of the specimen was evaluated. FE analyse of the representative test was carried out using the LS-DYNA explicit solver. The Johnson–Cook model and the material parameters include fracture strain derived from the former result were used for FE analyse. The strain gauge signals, DIC, and deformed shapes of the tensile specimen were used to validate the simulations.

2. Experimental procedures

2.1. Specimens

The chemical compositions of the high-strength, commercial sheet steels (DP700 and DP500) in this study are listed in Table 1. The specimens for microstructure characterisation were etched with 3% Nital for 10 s to provide enough contrast of ferrite and martensite under optical microscopy (OM). Fig. 1 shows the optical micrographs of microstructures of DP700 and DP500 steels. The volume fraction and grain size of ferrite and martensite were estimated by Image Tool Software. The average grain size and volume fraction of ferrite (d_α and f_α) and martensite (d_m and f_m) and the carbon content of martensite (C_m) are tabularized in Table 2.

The specimens for tensile tests were all prepared with electron discharge machining along the sheet rolling direction. The length–width surfaces of specimens were polished and the surface roughness value was $Ra = 1.6$ μm in average, while the value on the length-thickness surfaces (not polished) was $Ra = 3.2$ μm in average.

Currently there is no standardized specimen geometry for SHTB testing. The special specimen geometry design for SHTB is compromised between the two opposing aspects: a short gauge length to maintain stress equilibrium during the testing and a long gauge length results in a uni-axial stress state. A sheet-type specimen geometry with a gauge length of 6 mm, width of 4 mm, radius of fillet of 2 mm, and thickness of 1.8 mm was chosen according to a previous study on specimen geometry by Verleysen et al. [12] as well as the targeted of wide-range strain rate to be considered for the dynamic tests. The specimen was glued in grooves machined in the SHTB.

Table 1
Chemical compositions of the investigated steels (in wt%).

Steel	C	Si	Mn	P	S	Ni	Cr	Fe
DP700	0.11	0.18	0.44	0.023	0.03	2.68	0.97	Balanced
DP500	0.12	0.6	1.2	0.025	0.015	1.1	0.5	Balanced

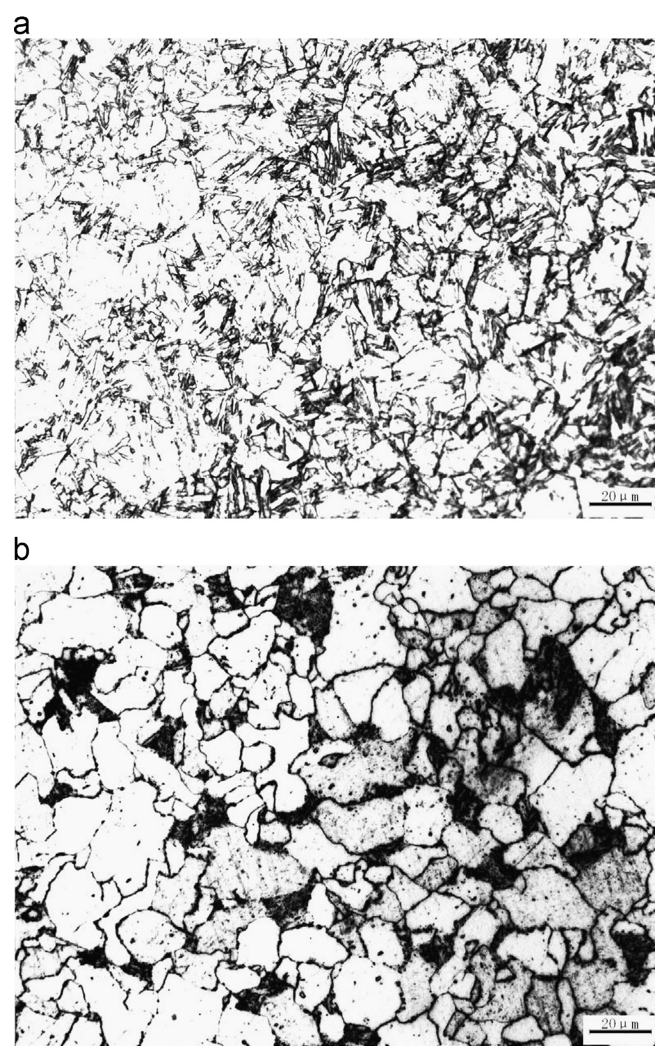

Fig. 1. The microstructures of (a) DP700 and (b) DP500. Ferrite appears in white, martensite in dark.