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Effects of pre-strain and bake-hardening on the crash properties of a top-hat section

L. Durrenberger[a,*], X. Lemoine[a], A. Molinari[b]

[a] ArcelorMittal Research, Voie Romaine, BP 30320, 57283 Maizières-lès-Metz Cedex, France
[b] Laboratory of Physics and Mechanics of Materials, LEM3, Université Paul Verlaine-Metz, Ile du Saulcy, 57045 Metz Cedex, France

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ABSTRACT

The effects of pre-strain on the crushing properties of a crash-box structure are reported for two Advanced High Strength Steels produced by ArcelorMittal (Dual-Phase DP600 and Transformation Induced by Plasticity TRIP780 steels). In addition, the effect of a bake-hardening treatment is studied on the TRIP780 steel. The material's behaviors have been determined in tensile loading in a wide range of strain-rates ($8 \times 10^{-3}\,\mathrm{s}^{-1} \le \dot{\varepsilon} \le 10^{3}\,\mathrm{s}^{-1}$) including strain-rate jump tests from quasi-static to dynamic loading. These interrupted tests allow us to characterize the effect of the (quasi-static) forming process on the subsequent dynamic behavior associated to the crash event. A phenomenological visco-plastic model, based on the evolution of an internal variable, has been implemented in PAMCRASH using a user-defined subroutine in order to simulate the crushing of the crash-boxes. A simple approach is proposed to account for the bake-hardening treatment in numerical simulations. A good correlation between experimental and predicted mean crush forces is obtained.

1. Introduction

One of the major challenges of the automotive industry is to reduce the structure weight, leading to a decrease of the CO_2 emission, while simultaneously improving the crash resistance. Today, more than 30% of the vehicle body is made of Advanced High Strength Steels (AHSS) which combine high mechanical properties and good formability.

The energy absorption capacity of a structure is characterized by the mean crush force appearing during the crash. As mentioned in Tarigopula et al. (2006), an increase of the impact velocity mass leads to an increase of the mean crush force and impact energy absorption which is due to strain-rate and inertia effects. For a given impact velocity and carrier mass, the absorption capacity of a structure depends mainly on: (i) the shape (ii) the wall thickness and (iii) the intrinsic mechanical properties of the material. For a given weight, the crash properties of a structure can be enhanced mainly by improving the material properties.

The forming process of a structure induces an evolution of the mechanical properties of the material (due to strain-hardening) and of the structure thickness. Thirion et al. (1998) have shown that the stamping process leads to an improvement of the crash properties of AHSS steels. Similar observations have been made by Abedrabbo et al. (2009) on AHSS steels formed by hydro-forming. In the present paper, the effects of pre-straining on the crash properties of a top-hat section (namely crash-box) structure are investigated for two multiphase steels (DP600 and TRIP780 steels) produced by ArcelorMittal. The additional effect of a bake-hardening treatment is also studied on the TRIP780 steel.

Since a crash event implies large localized strain-rates, a visco-plastic constitutive model has to be used. If the strain-rate sensitivity of the material is neglected, an under-estimation of the mean crush force is observed. The Johnson and Cook (1983) and Cowper and Symonds (1952) models are widely used in crash simulations. It has been shown in Durrenberger (2007) that the predictions of numerical simulations are not very sensitive to the type of visco-plastic constitutive model adopted. Using a numerical approach with LS-DYNA, Huh et al. (2003) have calculated the crash behavior of front side members and Thibaud et al. (2006) have studied the crash behavior of a TRIP700 steel. When the forming history is taken into account, both studies have shown that crash simulations have to be performed considering the history of the following local quantities: plastic strain, thickness reduction and residual stresses.

In this study, the visco-plastic model proposed by Durrenberger et al. (2008) has been used in order to account for strain-rate history effects. In addition, a numerical approach is proposed to take into account the bake-hardening treatment in finite element simulations using PAMCRASH.

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* Corresponding author. Tel.: +33 387 70 43 23; fax: +33 387 70 47 14.
E-mail address: laurent.durrenberger@arcelormittal.com (L. Durrenberger).

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2. Experimental approach

Two high strength steels produced by ArcelorMittal are studied here: a Dual-Phase DP600 steel and a TRansformation Induced by Plasticity TRIP780 steel. The loading history of a crash-box is composed of two phases. The first is the forming process which is generally performed under quasi-static loading. The second phase is characterized by a crash event. The pure dynamic behavior of the as-received material and the effects of a strain-rate jump test (from quasi-static to dynamic loading) have been investigated. The influence of pre-straining on the crash properties have been studied for both steels and the effects of a bake-hardening treatment have been investigated for the TRIP780 steel.

Tensile characterizations were performed at room temperature using three experimental methods. The quasi-static behavior ($\dot{\varepsilon} < 0.1\,\mathrm{s}^{-1}$) was determined by a conventional screw controlled Zwick Z150 machine, equipped with an optical Messphysik extensometer and a HBM-150 Z4 load cell. For the intermediate strain rates ($0.1\,\mathrm{s}^{-1} \leq \dot{\varepsilon} \leq 100\,\mathrm{s}^{-1}$), a hydraulic machine was used. The force and sample elongation are measured by a piezoelectric 400 kN KISTLER load sensor (pre-loaded at 130 kN) and a laser sensor which measures the displacement of the moving grip. The range of strain rates higher than $10^2\,\mathrm{s}^{-1}$ was reached with a tension split Hopkinson bar build according to the principle of Albertini and Montagnani (1974). Elastic deformations were measured versus time in the bars with strain gauges, and these measurements were used to calculate the elongation, force and rate of elongation of the specimen, employing one-dimensional elastic wave theory proposed by Lindholm and Yeakley (1968).

2.1. Strain-rate jump tests

The effects of a strain-rate jump test have been investigated on both multiphase steels. It has been shown by Frantz and Duffy (1972) that the material response after a strain-rate jump test is microstructure dependent. In BCC (respectively FCC) metals, a dynamic loading following a quasi-static pre-strain leads to an increase (respectively decrease) of the flow stress compared to the pure dynamic tensile curve.

Dual-Phase steels are composed of martensitic islets dispersed in a ferritic matrix. The dislocation density is initially non uniform. As mentioned by Korzekwa et al. (1984), dislocation cells are arranged around the martensitic islets because the ferrite phase has to accommodate the volume variation of the martensite during the cooling phase of the manufacturing of the steel. This accommodation is performed by plastic deformation of the ferrite phase, which explains that the dislocations cells are created at the interface. Byun and Kim (1993) have shown that the plastic deformation process depends on the dimensions of the martensitic islands, which are very hard metallurgical elements (mean ~ 60 HRC according to Hildenwall (1979)). All phases are first deformed elastically. Then, the martensitic phase continues to be elastically deformed whereas the ferrite phase is deformed plastically; the dislocation cells are propagating from the interface to the interior of the ferrite grains. Rashid and Cprek (1978) have shown that if martensitic islands are small, they are not plastically deformed and can be described as rigid particles dispersed in a ferritic matrix, whereas if their dimensions are bigger a plastic deformation can occur after excessive elongation of the ferrite phase. It appears that the presence of the martensite plates explains the high stress level of these steels but the hardening is mainly controlled by the evolution of the ferrite phase. As a result, the effect of strain-rate history on Dual Phase steels, Fig. 10, is typical of the behavior of BCC metal.

The microscopic processes occurring in BCC steels during a strain-rate jump test have been explored by Uenishi (2003) who performed TEM observations on solution-hardened steels deformed at high ($10^3\,\mathrm{s}^{-1}$) and low ($10^{-3}\,\mathrm{s}^{-1}$) strain-rates. It was shown that an increase of strain-rate leads to higher dislocation density (especially at low strains) and delays the onset of dislocation organization. During a jump of strain-rate following a quasi-static pre-straining, the dislocation density increases inside an organized structure, leading to a high macroscopic work-hardening rate $\partial\sigma/\partial\varepsilon$ just after the jump.

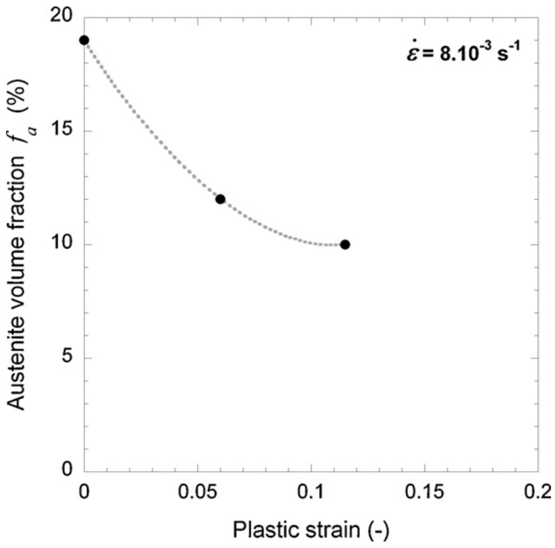

Fig. 1. TRIP780 steel: evolution during a quasi-static tensile test of the austenite volume fraction as a function of the plastic strain (dots are experimental data determined via interrupted tests).

The microstructure of TRIP steels is composed of soft ferrite grains with bainite and retained austenite. The retained austenite (mean ~ 30 HRC according to Hildenwall (1979)) transforms into martensite during deformation. The evolution of the ferrite microstructure and the growth of the martensite volume fraction f_M are mainly responsible of the increasing stress during deformation. Fig. 1 provides the evolution of the volume fraction of austenite f_A in terms of the plastic strain for a quasi-static tensile loading. No experimental data are available at high strain-rate because all specimens were fractured during the test with tension split Hopkinson bars. The evolution of the volume fraction of martensite is given by: $f_M = f_A^0 + f_M^0 - f_A$ where f_A^0 and f_M^0 are respectively the initial volume fractions of austenite and martensite. According to the model proposed by Tomita and Iwamoto (1995), there is no martensitic transformation under dynamic loading at room temperature. If the evolution of f_A and f_M are considered frozen, the overall plastic response is mainly governed by the deformation of the ferrite phase (BCC structure) and the macroscopic response of the TRIP steel would be typical of a material with BCC structure. This behavior has been observed by Bleck et al. (2006) on a TRIP700 steel with 11% of initial volume fraction of austenite.

For the TRIP780 steel studied in this paper, the initial volume fraction of austenite is 19% and an atypical behavior is observed. A dynamic tensile loading following a quasi-static deformation provides a decrease of the flow stress compared to the pure dynamic loading curve. As a result, the macroscopic response of the TRIP steel appears to be governed by the evolutions of both the ferrite (BCC) and austenitic (FCC) phases if the austenitic phase has a non negligible volume fraction.

2.2. Effects of a bake-hardening treatment on mechanical properties

The bake-hardening (commonly called BH) treatment corresponds to strain aging, which is the result of an interaction between