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Hot tensile and expansion tests of Ductibor®1000 steel

N Demazel¹, A Boyer^{1,2}, H Laurent¹ and M C Oliveira²

¹Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56321 Lorient, France

²CEMMPRE, Department of Mechanical Engineering, University of Coimbra, Polo II, Rua Luís Reis Santos, Pinhal de Marrocos, 3030-788 Coimbra, Portugal

E-mail: nathan.demazel@univ-ubs.fr

Abstract. The boron steels present high mechanical properties which are of great interest for lightening the vehicle parts. But these steels, as the Ductibor®1000, need to be hot formed. The hot stamping process consists of a heating/austenization step leading to an increase of the formability, followed by simultaneous forming and quenching steps. In order to understand the thermomechanical and metallurgical cycles occurring during this process, this study focuses on two different test devices at high temperatures using direct resistance heating: a Gleeble 3500 machine for tensile tests and a new bulge test device. The two different tests were performed on the Ductibor®1000 steel for a temperature of 900°C (with temperature holding during deformation) after an austenization step, which consists of heating up to 900°C and a temperature holding stage. The stress-strain curves of the tensile tests obtained using Digital Image Correlation (DIC) are compared to the stress-strain curves of the bulge tests obtained using a laser profilometer and the membrane theory.

1. Introduction

In order to reduce greenhouse gas emissions, the car manufacturers look for lighter vehicles while maintaining high safety standards. The quenchable steels with their high mechanical properties can respond to these requests. The hot stamping process allows to produce parts with these quenchable steels, as described in detailed in [1,2,3]. It consists of an austenization step at high temperature followed by simultaneous forming and quenching steps in a press to obtain high tailored properties [4].

Some devices were developed to perform tests over the temperature range in the austenitic state, mainly to evaluate the forming limit curve (FLC). In their work, Shao et al. [5] proposed an adaptation to the Gleeble machine using cruciform specimens. Thanks to the resistance heating integrated in the Gleeble machine, the test can be performed up to a maximum temperature of 1000 °C. Li et al. [6] used Nakazima tests to characterize the 22MnB5 steel at 600 and 700 °C. Turetta et al. [7] and Bariani et al. [8] developed a device to simulate thermomechanical cycles occurring during hot stamping process thanks to an induction heating of the sheet, a punch with cartridges heaters and compressed air jets for cooling and quenching. This device enables evaluating the FLC of high-strength steels (HSS) at temperatures up to 900 °C under hot stamping conditions.

The major mode encountered in many sheet forming processes is the biaxial stress mode. Some works proposed to evaluate the stress-strain curves in warm and hot conditions in this mode using hydraulic bulge test devices. Li et al. [9] investigated the formability of the AZ31 magnesium alloy using a bulge test device and pulse current to heat a rectangular sheet at 400 °C. In their work, Braun et al. [10,11,12] developed a hot gas bulge test device with resistance heating of rectangular sheets to characterize quenchable steels up to 900 °C.

In this paper, a bulge test device using resistance heating to characterize metal sheets up to 900 °C is presented. This bulge test device differs from others reported in literature because it is possible to test specimens at very high temperature considering a constant temperature during the deformation, which is carried out by pressure of a gas and therefore without friction. The material studied is a Ductibor®1000 steel. Since it is still little studied, this material is succinctly described. Contrary to Usibor® steels, Ductibor® steels offer a high ductility which leads to a very good impact behaviour. Then, the hot bulge test device developed and its principle are presented. The method using a laser profilometer to evaluate the stress-strain curves is described. This method is validated with a comparison to a digital image correlation method (DIC method) on a EN AW6061-T6 aluminium alloy. Finally, the stress-strain curves of the Ductibor®1000 resulting from hot gas bulge tests and a tensile test are given for a forming temperature of 900 °C.

2. Method

2.1. Material

The material studied is the Ductibor®1000 sheet with a thickness of 0.8 mm and a protective layer composed of 90 wt. % aluminium and 10 wt. % silicon. Its chemical composition is given in Table 1.

Table 1: Chemical composition (wt. %) of Ductibor®1000 (ArcelorMittal)

Max. C	Max. Si	Max. Mn	Max. P	Max. S	Al	Max. Ti	Max. Nb	Max. Cu	Max. B	Max. Cr
0.10	0.6	1.8	0.03	0.01	0.01 - 0.1	0.05	0.10	0.20	0.005	0.20

2.2. Experimental device

The basic diagram of the hot bulge test principle is shown in **Figure 1.a**. First, the circular blank is clamped on its periphery between the die and the blank-holder. Then, the blank is heated using resistance heating. Finally, the gas pressure is applied to form the bulge while the temperature is maintained [13].

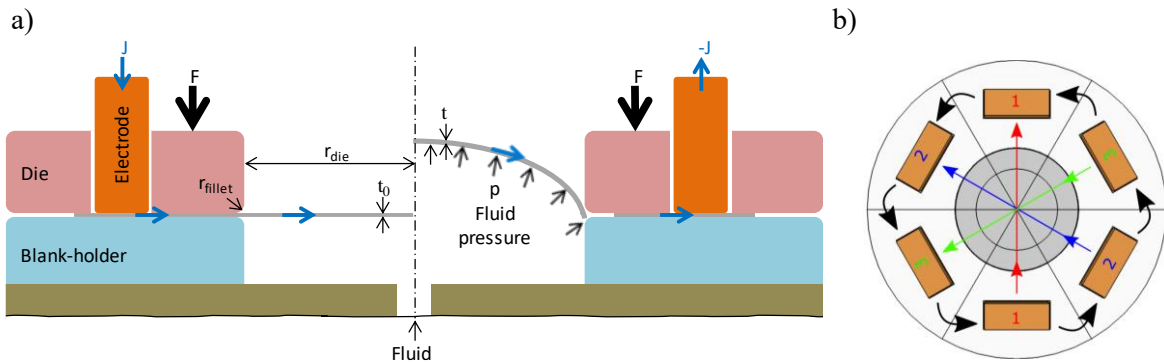


Figure 1: Basic diagram of a) the hot gas bulge test and b) the rotary permutation of active electrode pair.

The resistance heating system is composed of a multi-electrodes system to apply the electrical current to the blank. This system allows a good temperature homogeneity thanks to a rotary permutation of the electrical field, as shown in **Figure 1.b**. Pneumatic cylinders associated to each pair of electrodes ensure the permutation. The alternative current is provided by an electrical generator, which is supplied by two phases of the three-phase network at 400 V, 200 A, i.e. 80 kVA. The measured root mean square current (RMS current) during heating does not exceed 6000 A and the maximum measured voltage at the electrodes is about 5 V for a maximum power of 22 kW. The applied current is managed by a temperature control loop using a 250 μ m diameter K-thermocouple welded at 10 mm from the blank centre. Others K-thermocouples can be welded at 20, 30 and 40 mm from the centre to monitor the temperature uniformity. The tools are placed in the Instron 8803 tensile machine, which applies a

clamping force of 300 kN. These tools are electrically isolated from the blank and the electrodes with Miglasil® mica sheets and Kapton® adhesive tapes. The gas pressure is ensured by a 200 bar argon tank associated with a control system, composed of a TESCOM ER5000 controller and a 0-70 bar pressure sensor placed in the cavity under the blank. Concerning the evaluation of the stress-strain curve, the use of a DIC system is more difficult at high temperature, due to the pattern deterioration and contrast losses during bulge test. Thus, the KEYENCE LJ-V7200 laser profilometer is used to monitor the maximum dome height of a line passing through the blank centre and the stress is calculated using the membrane theory. More details about the stress-strain evaluation are given in the next section.

2.3. Stress-strain curves determination

To evaluate the stress-strain curve based on the results obtained with the laser profilometer, there are three key variables, the maximum height of the dome monitored by the laser profilometer, the measured pressure and the initial thickness. The membrane theory is used to determine the stress.

According to the ISO 16808:2014 standard [14], the bending can be neglected if the ratio of the thickness to the diameter of the tool is less than 1/33 ($r_{\text{die}} = 60$ mm and $t_0 = 0.81$ mm), leading to the assumption that the stress component normal to the surface is equal to zero at the centre of the blank. Another assumption used in the ISO 16808:2014 standard, is that, at the dome apex, the stress state is assumed equibiaxial. Moreover, the curvature radii at mid-thickness are the same in all directions. Thus, the biaxial stress σ_b is determined using the following form of the membrane theory:

$$\sigma_b = \frac{p\rho}{2t} \quad (1)$$

where p is the applied pressure, t is the thickness of the sheet at the dome apex, which is calculated by the Hill relation [15]:

$$t = t_0 \left(1 + \left(\frac{h}{r_{\text{die}}} \right)^2 \right)^{-2} \quad (2)$$

and ρ is the curvature radius of the dome, defined by the Panknin formula [16] using the dome height h , the die radius r_{die} and the fillet radius of the die $r_{\text{fillet}} = 5$ mm (see these dimensions in Figure 1.a):

$$\rho = \frac{(r_{\text{die}} + r_{\text{fillet}})^2}{2h} + \frac{h}{2} - r_{\text{fillet}} \quad (3)$$

The biaxial strain is calculated from the thickness strain:

$$\varepsilon_b = -\ln \left(\frac{t}{t_0} \right) \quad (1)$$

In the case of the complete DIC method, the curvature radius is determined via a sphere fitted to the surface and the thickness is calculated using the volume constancy condition during plastic deformation. More details are given in [17].

3. Results and discussion

3.1. Validation of the method using laser profilometer

As written in the first section, the DIC system is hard to use at high temperature, because of the pattern deterioration and the loss in the contrast quality. Thus, to avoid these issues, another system using a laser profilometer is used to determine the stress-strain curve. The method proposed to be used with the laser profilometer was tested for the EN AW6061-T6 at 150 °C. The results are compared to those calculated using two other methods. One is referred as the complete DIC method, since both the radius of curvature and the thickness are evaluated based on data from DIC. The other, based on the method using laser profilometer, uses the evolution of the dome height extracted from DIC data and equations (2-4). Finally, the results obtained from a tensile test performed on a Gleeble machine using a DIC system are also discussed. All these results are shown in Figure 2. Globally, there is a good agreement between the stress-strain curves resulting from the bulge tests, i.e. using the three methods. Concerning

the tensile test results, the stress level is lower than the one resulting from the bulge tests. Nevertheless, this can be due to the difference on the strain rate levels attained for each type of test, given that the EN AW6061-T6 presents a positive strain rate sensitivity at high temperature [18]. The tensile test is performed with a strain rate of 2.10^{-3} s^{-1} while the bulge tests start at a strain rate of 1.10^{-3} s^{-1} that increases up to 8.10^{-3} s^{-1} .

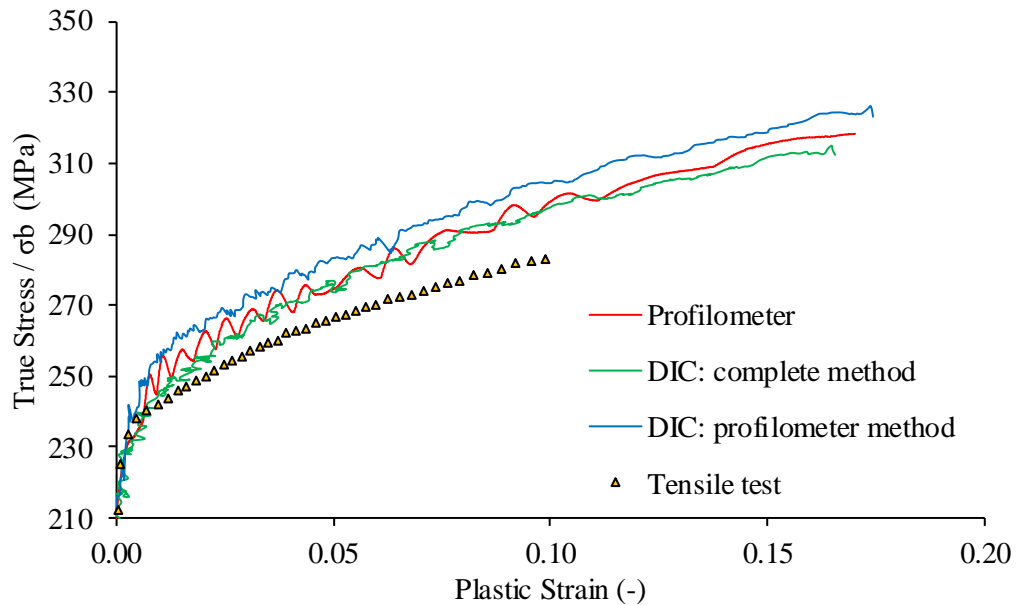


Figure 2: Stress-strain curves of the EN AW6061-T6 at 150°C, obtained from a bulge test and the proposed method using a laser profilometer, complete DIC method, the evolution of the dome height from the DIC system and equations (2-4), and from a tensile test using DIC system.

3.2. Temperature uniformity during the bulge test

Figure 3 shows the temporal evolution of the temperature at 10, 20, 30 and 40 mm from the blank centre, the set temperature and the pressure applied to form a Ductibor®1000 blank during bulge test at 900°C. The blank centre reached 900 °C in 60 s and the bulge test occurred between 80 and 107 s with a good temperature uniformity. The maximum temperature difference did not exceed 30 °C up to 40 mm radius. The temperature drop at 100 s for thermocouple located at 40 mm (TC40mm) was due to its dissociation from the blank.

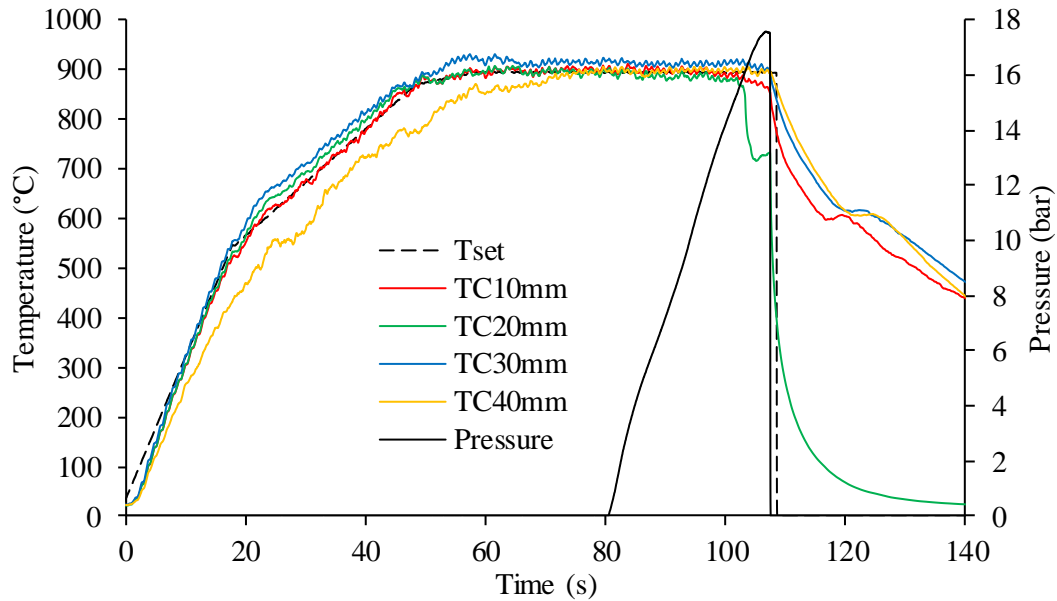


Figure 3: Temporal evolutions of the temperature at 10, 20, 30 and 40 mm from the blank centre and temporal evolution of the pressure for a forming test at 900 °C.

3.3. Stress-strain curves at 900 °C

The stress-strain curves of three bulge tests and a tensile test performed at 900 °C are presented in

Figure 4. The bulge tests 2 and 3 were aborted contrary to the bulge test 1, for which the ramp pressure (shown in Figure 3) led to a burst. The uniaxial test was performed until the rupture. At the austenitic state, the quenched steel presents an isotropic behaviour [19], thus the uniaxial tensile test and the bulge tests results are compared with the same assumption. The biaxial stress level is lower than the uniaxial stress level and the strain level before rupture is higher for the bulge test 1. However, the comparison of the stress-strain curves between the bulge and the uniaxial tests is biased by the strain rate difference. A positive strain rate sensitivity was observed for the Ductibor®1000 at high temperature, using tensile tests performed on a Gleebe machine and as for the Usibor®1500P [19]. In the case of the tensile test, the strain rate is around 2.0 s^{-1} while for the bulge tests the strain rate begins at around 1.10^{-3} s^{-1} and increases up to 8.10^{-2} s^{-1} , as shown in

Figure 5 for the bulge test 1.

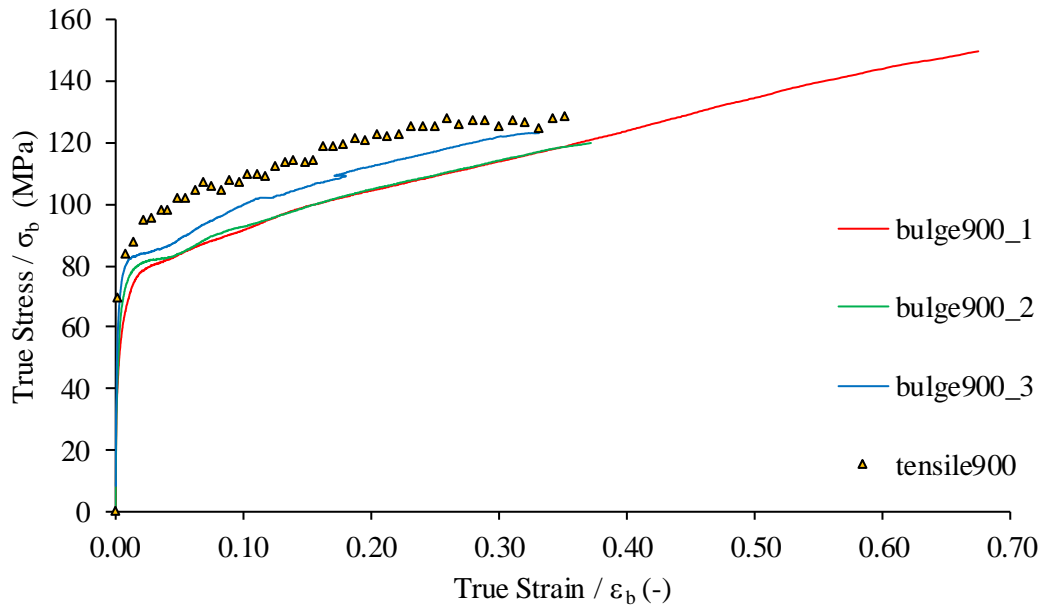


Figure 4: Stress-strain curves of Ductibor®1000 for three bulge tests and a tensile test at 900°C.

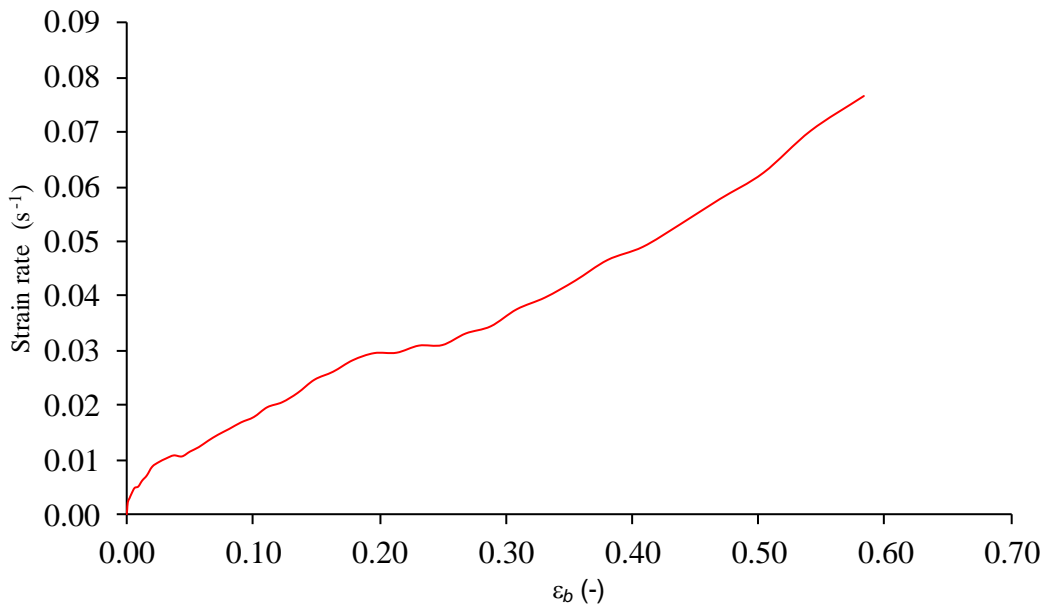


Figure 5: Strain rate as a function of the biaxial strain during the bulge test 1.

4. Conclusion

This paper presents an innovative hot gas bulge test, which allows to perform tests at high temperature up to 900 °C, with a good temperature uniformity at the blank centre thanks to a multi-electrodes system for resistance heating. Due to difficulties to obtain the deformations at high temperatures with a DIC system, another method to determine stress-strain curves using the membrane theory and a laser profilometer was validated with bulge tests performed with EN AW6061-T6 blanks at 150 °C. The proposed method is used to determine stress-strain curve at high temperatures. The results presented show a good agreement between stress-strain curves of Ductibor®1000 blanks resulting from bulge tests and a tensile test performed at 900 °C.

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