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Mechanical properties determination of dual-phase steels using uniaxial tensile and hydraulic bulge test

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Abstract

Numerical simulations of sheet metal forming processes need the establishment of highly reliable results, which in turn need the accurate identification of mechanical properties. In this paper a study is presented on the choice of the characterization function of flow stress-strain curve of sheet metal materials, as well as the selection of the best yield locus, based on experimental uniaxial tensile and biaxial hydraulic bulge tests performed on dual-phase steels of industrial interest. To obtain a better characterization of the hardening curve, a combination is made using the uniaxial tensile test data with biaxial hydraulic bulge test results, since bulge test covers a larger range of plastic strain when compared to tensile test. Since the two flow curves have different strain paths, they can’t be directly compared or combined. Therefore, it is necessary a transformation of flow stress-strain curve provided from biaxial bulge test into equivalent stress-strain curve. Different methodologies were applied to transform biaxial stress-strain curve to an equivalent one and the different results are compared and evaluated.

Keywords: Sheet metal forming; dual-phase steels; flow curve; biaxial hydraulic bulge; yield locus.

1. Introduction

The accuracy of the results obtained by numerical simulation depends, among other factors, on the characterization of mechanical properties of materials and particularly on its hardening curve. The selection of the constitutive model, which better reproduces the material behaviour, has an important influence in such accuracy of results. The uniaxial tensile test is the most common method to obtain the characterization of the material and corresponding flow stress-strain curve is expressed in a state of uniaxial stress. However, this type of test has the limitations of uniaxial loading, corresponding to lower values of uniform and maximum fracture strains when compared to those obtained by other types of loadings, which are included in most of sheet metal forming processes. Therefore, these results need to be extrapolated when modelling material hardening behaviour, e.g., when using numerical simulation. One possible approach to obtain higher strain information for metallic material behaviour and its hardening curve is to use the hydraulic bulge test [1-3], since it allows higher values of plastic deformation. Some authors are also using a viscous material instead of hydraulic fluid [4,5]. In this paper, it is proposed a methodology to obtain the hardening curve of dual-phase steels (DP500, DP600 and DP780) based on the combination of two parts. The first part of the data is obtained by the uniaxial tensile test, characterizing the material to lower values of deformation, and the second part corresponds to the biaxial equivalent stress-strain curve obtained from hydraulic bulge test. Making use of the experimental results it will be also selected the yield locus that

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better reproduces the behaviour of the materials under study.

2. Mechanical Characterization

2.1. Uniaxial tensile test

The uniaxial tensile tests were performed at room temperature with grip speed of 5 mm/s, corresponding to a strain rate of 0.0016 s^{-1}. The samples, with a thickness of 0.8 mm, were obtained by machining, according to ASTM E 8M-04, for three different directions relative to the rolling direction (0°, 45° and 90°). In order to ensure the repeatability of the results, several experiments were performed for each direction and material. The respective true stress-strain curves for the selected materials and directions are shown in Fig. 1.

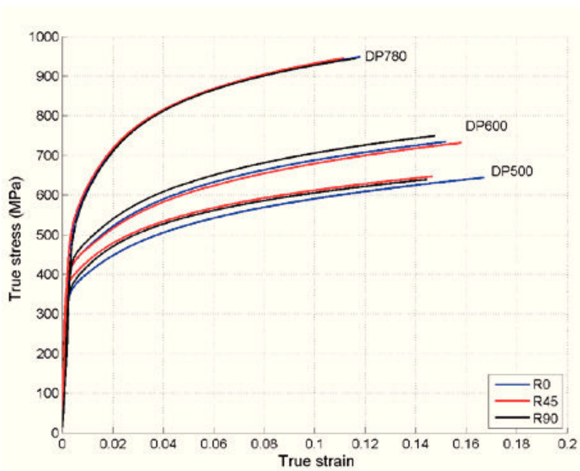

Fig. 1. Flow stress-strain curve obtained from uniaxial tensile test for selected dual-phase steels, according to different directions relative to the rolling direction.

Table 1 presents some mechanical properties obtained from flow stress-strain curves, such as the yield stress ($R_{P0,2}$), ultimate tensile strength (R_m), elongation at yield point (e_0), uniform elongation (e_u) and total elongation (e_t).

Table 1. Mechanical properties of different materials, obtained from uniaxial tensile test (rolling direction).

Material	$R_{p0,2}$ (MPa)	R_m (MPa)	e_0 (%)	e_u (%)	e_t (%)
DP500	356.53	544.84	0.34	18.18	29.52
DP600	416.05	630.85	0.37	16.40	27.14
DP780	526.18	843.10	0.47	12.53	17.96

2.2. Hydraulic bulge test (biaxial)

The experimental system to perform the hydraulic bulge test is composed of a set of tools, a hydraulic pump and a mechanical device, which gets the relevant data for material characterization (Fig. 2).

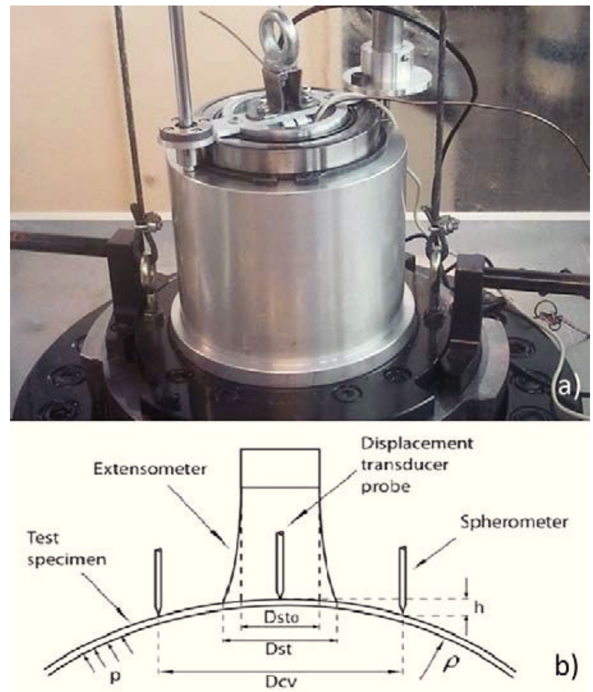

Fig. 2. a) Measuring system, b) variables used to determine the stress and biaxial strain.

The set of tools contains a circular die, with a nominal diameter of 150 mm, a die radius of 13 mm and a blank holder with a drawbead, which restricts the sample and avoids any oil leakage during the test. The measuring system is calibrated before each test in order to ensure accuracy and reproducibility of the measured values. The bulge test is performed with a pressure increment of 1 bar/s and the circular samples have a 250 mm diameter. The experimental system allows the continuous acquisition of hydraulic pressure (p), as well as the variables provided by the measuring system: radius of curvature (ρ) and biaxial strain (ε). The ratio blank diameter/thickness permits the application of the membrane theory and the biaxial stress (σ) is calculated by Eq. 1 while biaxial strain uses Eq. 2.

$$\sigma = \frac{p \cdot \rho}{2 \cdot t} \tag{1}$$

$$\varepsilon_t = 2 \cdot \ln\left(\frac{D_{st}}{D_{st_0}}\right) \tag{2}$$

Using the values of the different variables obtained during the bulge test (Fig. 2 b)), the radius of curvature is determined by Eq. 3, while the thickness of the sample can be obtained by Eq. 4, knowing the initial thickness (t_0) and the strain in thickness (ε_t).

$$\rho = \frac{\left(\frac{D_{cv}}{2}\right)^2 + h^2}{2 \cdot h} - \frac{t}{2} \quad (3)$$

$$t = t_0 \cdot e^{-\varepsilon_t} \quad (4)$$

Table 2 contains the burst pressure obtained in hydraulic bulge test, as well as the total height at the pole for each material.

Table 2. Mechanical properties of different materials obtained by hydraulic bulge test.

Material	Burst pressure (bar)	Total height at the pole (mm)
DP500	87.21	49.52
DP600	97.62	50.05
DP780	119.61	42.04

The hydraulic pressure reached during the experimental test was about 95% of burst pressure of the material, due to the uncertainty of the robustness of measuring system during the "explosion" of the hydraulic fluid at bursting [6]. The respective biaxial stress-strain curves for the selected dual-phase steels and directions are shown in Fig. 3.

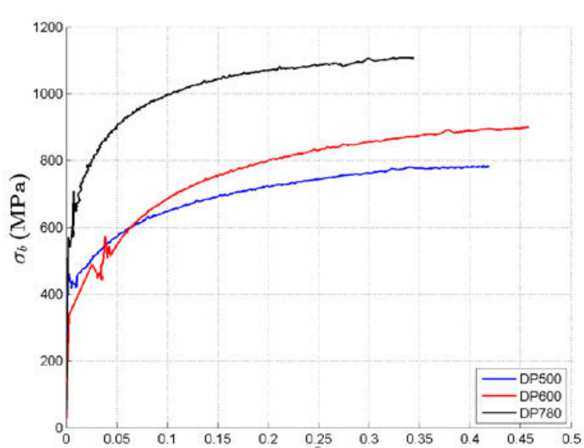

Fig. 3. Biaxial stress-strain curves for different materials obtained by hydraulic bulge test.

2.2.1. Transformation of biaxial stress-strain curve in the equivalent stress-strain curve

After the mechanical characterization tests (uniaxial tensile and hydraulic bulge) there are two hardening curves for the same material, where σ=f(ε) comes from the uniaxial tensile test, according to the rolling direction, and σ_b=f(ε_b) comes from hydraulic bulge test. Since the obtained curves are not in the same space of deformation, they cannot be directly compared and so the combination of the data cannot be performed. Therefore, a transformation of the biaxial stress-strain curve in equivalent stress-strain curve, using the equivalent plastic work, is required. Assuming the incompressibility of the material and considering the state of stress at the pole as $\sigma_1=\sigma_2=\sigma_b$, using the relationship of equivalent plastic work ($\sigma \cdot \varepsilon = \sigma_1 \cdot \varepsilon_1 + \sigma_2 \cdot \varepsilon_2$) and Levy-von Mises equations, we get:

$$\frac{\sigma}{\sigma_b} = \frac{\varepsilon_b}{\varepsilon} = k \quad (5)$$

where k is a constant.
The equivalent plastic work is the link between the two curves, being W_u the plastic work per unit volume for the tensile test and W_b for the hydraulic bulge test. This methodology has been used by other authors with satisfactory results [4,7,8]. Integrating σ=f(ε) for all the plastic domain, one obtains the corresponding plastic work per volume unit for both of tests, being defined by Eq. 6.

$$W(\varepsilon) \approx \sum_{i=i(\varepsilon_i)}^{i=i(\varepsilon_f)-1} \left(\varepsilon_{i+1} - \varepsilon_i\right) \cdot \frac{\sigma_{i+1} - \sigma_i}{2} \quad (6)$$

When $W_u=W_b$ it is possible to establish a relationship between the stresses or strains for both tests, i.e.:

$$\begin{cases} \sigma \rightarrow W_u = W_b = \sigma_b \\ \varepsilon \rightarrow W_u = W_b = \varepsilon_b \end{cases} \quad (7)$$

For the determination of k parameter, various methods can be considered [4,7,9]. In this article, it will be used a method based on the equivalent plastic work, corresponding to the maximum values of stress and strain of the uniaxial tensile test. As shown in Fig. 4 [4], the maximum stress of tensile test (blue curve) have a corresponding equivalent plastic work (green line) of 90 mJ/mm^3, approximately. The intersection of the green line (W=90 mJ/mm^3) with the biaxial test (red curve) gives the corresponding biaxial stress point used to obtain the k parameter. For the same value of equivalent plastic work, we have a pair of stresses ($\sigma_{max} \rightarrow W_u = W_b \rightarrow \sigma_b \Rightarrow k = \sigma_{max}/\sigma_b$).

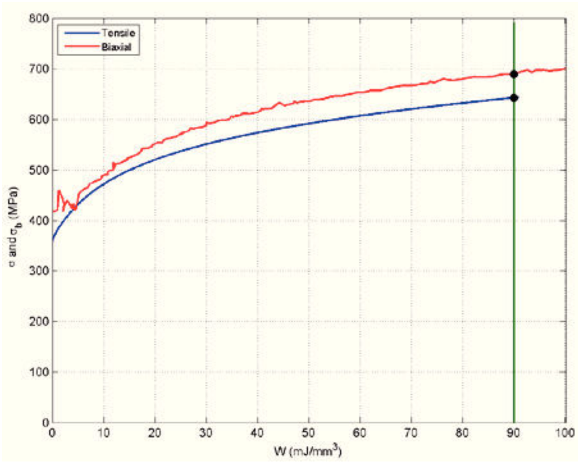

Fig. 4. Relationship between the plastic work and the stresses of both tests for the case of maximum stress of the tensile test.

Table 3 presents the values of *k* parameter, for each material, which transform the biaxial stress-strain curve into equivalent stress-strain curve.

Table 3. Parameter k used to transform the biaxial into equivalent stress-strain curve.

Material	DP500	DP600	DP780
k	0.9318	0.9645	0.9423

Fig. 5 presents the transformations of the biaxial stress-strain curve into equivalent stress-strain curve and the corresponding extrapolation of tensile data using bulge test data for each material.

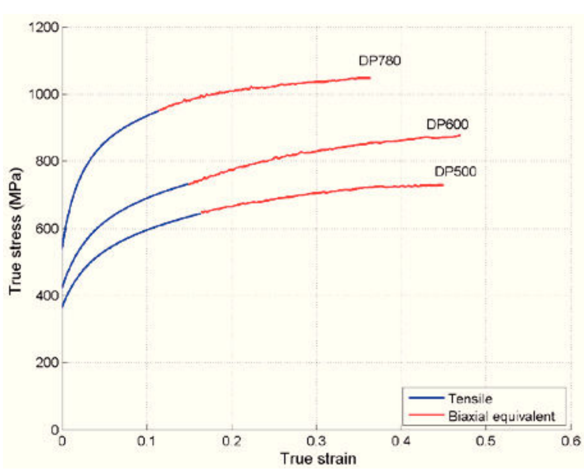

Fig. 5. Combination of the stress-strain curve of tensile test and the equivalent stress-strain curve of bulge test, for each material.

3. Yield Locus

The yield criteria describes the plastic behaviour of a material from the macroscopic point of view, the accuracy being related with a properly defined yield surface reproducing the plastic behaviour of the isotropic or anisotropic material. In order to know such behaviour, experimental tests were performed with the objective to determine the anisotropy coefficients of selected dual-phase steels. Table 4 presents the anisotropy coefficients (r) for different directions relative to rolling direction.

Table 4. Anisotropy coefficients for different directions relative to the rolling direction, for each material.

Material	r_0	r_{45}	r_{90}
DP500	1.02	0.87	1.20
DP600	0.62	1.03	0.80
DP780	0.70	1.05	0.88

The yield criteria for anisotropic materials were successively introduced by several authors. In this article some classic models are presented, such as those proposed by Hill in 1948 [10] and Barlat *et al.* in 1989 [11]. Figs. 6, 7 and 8 show the respective yield locus for the studied materials, by using two methods to obtain the yield criteria parameters: one based on the anisotropy coefficients (r-value based – H48-R and Yld89-R), and the other using the yield stresses (stress based – H48-S-R0 for rolling direction, H48-S-R90 for transverse direction and Yld89-S).

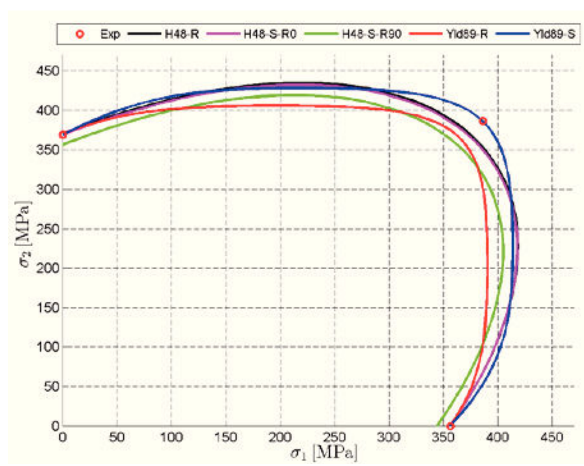

Fig. 6. Yield locus for DP500, using Hill '48 and Yld89.

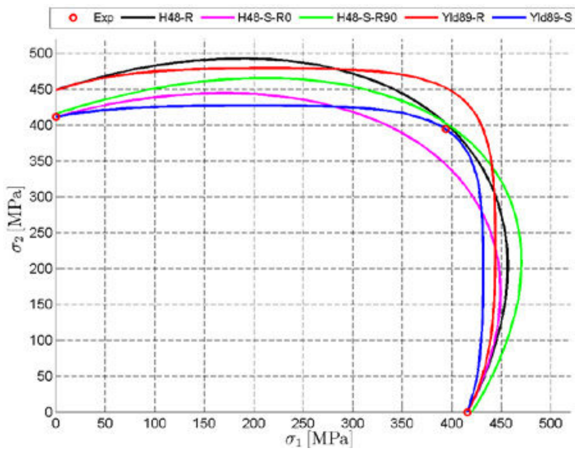

Fig. 7. Yield locus for DP600, using Hill '48 and Yld89.

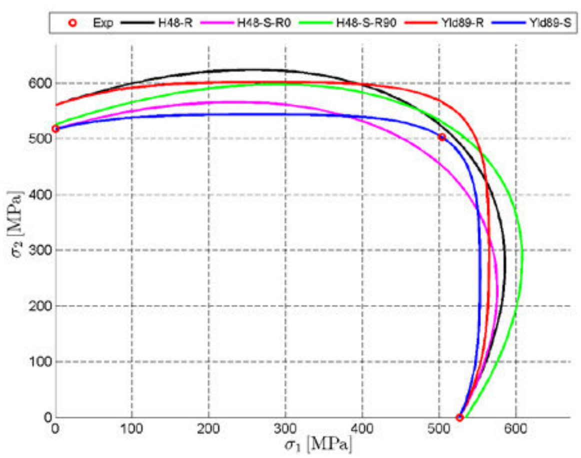

Fig. 8. Yield locus for DP780, using Hill '48 and Yld89.

4. Conclusions

This paper describes the methodology to obtaining the hardening curve of dual-phase steels (DP500, DP600 and DP780), based on the hydraulic bulge test results combined with uniaxial tensile flow curve. An approach is presented for the transformation of biaxial stress-strain curve to equivalent stress-strain curve, which is based on equivalent plastic work corresponding to the maximum values of stress and strain of tensile test. The combination of tensile test data with the results from the hydraulic bulge test proved to give excellent results in the characterization of material behaviour for higher values of plastic strain. Two yield criteria are considered and the closest results to the experimental values were obtained from Yld89-S criteria, whose criteria parameters are determined using the yield stress for different directions. It was observed that the choice of method for the determination of yield criteria parameters influences the shape of yield surface.

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