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A pure bending machine to identify the mechanical behaviour of thin sheets

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ABSTRACT: It is now commonly accepted that the so-called Baushinger effect has to be taken into account for accurate springback predictions during sheet metal forming simulations. Baushinger effect can be modelled through the introduction of a kinematic hardening law in the material model.

The identification of such a behaviour requires to perform tests such that the material is subjected to reversal loadings. In the case of thin sheets, tension-compression tests are impossible because of buckling. Two alternative solutions can be found in the literature: shear tests and bending tests. Since bending tests are more representative of the behaviour of the material during many industrial metal forming processes, several authors (see for example [1-2]) have recently proposed bending machines for such applications.

This paper is devoted to the presentation of an original pure bending machine developed at LMT-Cachan (patent pending 2002 [3]). The machine architecture and kinematics is presented. It enables to bend specimens up to 90° (i.e. 13% strain at the surface of a 1 mm thick and 6 mm long specimen). The bending moment is simultaneously applied to two identical specimens so that no spurious "normal" and "shear" loads are applied to the specimens as experimentally verified through the measurement of moments in different points of the machine. Strain fields can be obtained directly from strain gauges glued on the specimens or from the motors angle and the compliance of the machine.

The capabilities of this original pure bending machine are illustrated herein by tests performed on different materials including a 0.25 mm thick TRIP steel sheet.

Key words: bending, testing machine, identification, metal sheet, kinematic hardening

1 INTRODUCTION

In order to predict with a high accuracy the springback in case of reversal bending, it is impossible to neglect the kinematic hardening. To identify this kinematic hardening from classical uniaxial tests, the specimen must be subjected to compression. Such a compressive test is impossible on thin sheets (thickness under 1mm) because of buckling. One solution is to perform a bending test and to identify the behaviour in compression by an inverse analysis. The simulations used for the inverse analysis are all the more accurate as the specimen is subjected to pure bending i.e. without tension and shear.

Pure bending is generally obtained by four-point bending. The maximum curvature that can be reached with this solution is so limited that maximum strain may be very limited for thin sheets. To overcome this problem, different original bending machines have been recently proposed in the literature [1,2], but all these architectures induce some sort of friction in linkages and hence spurious forces normal and shear loads on the specimen.

An original machine that enables one to perform pure bending tests on thin sheets has been developed within Brite-EURAM project FORMAS. The maximum value of the angle α (see Fig. 1) that can be reached with this machine is 90°. For instance, this value corresponds to a value of 13% for the maximum strain in the case of a 1 mm thick and

6 mm long specimen. This machine has been patented [3].

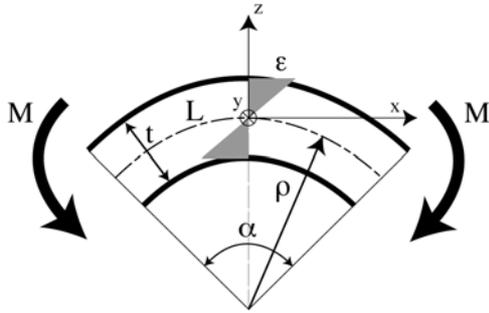


Fig. 1. Pure bending.

The inverse analysis that can be used to identify the constitutive laws from bending and tension tests has been applied to a 1 mm thick non-alloyed eutectoid steel sheet [4].

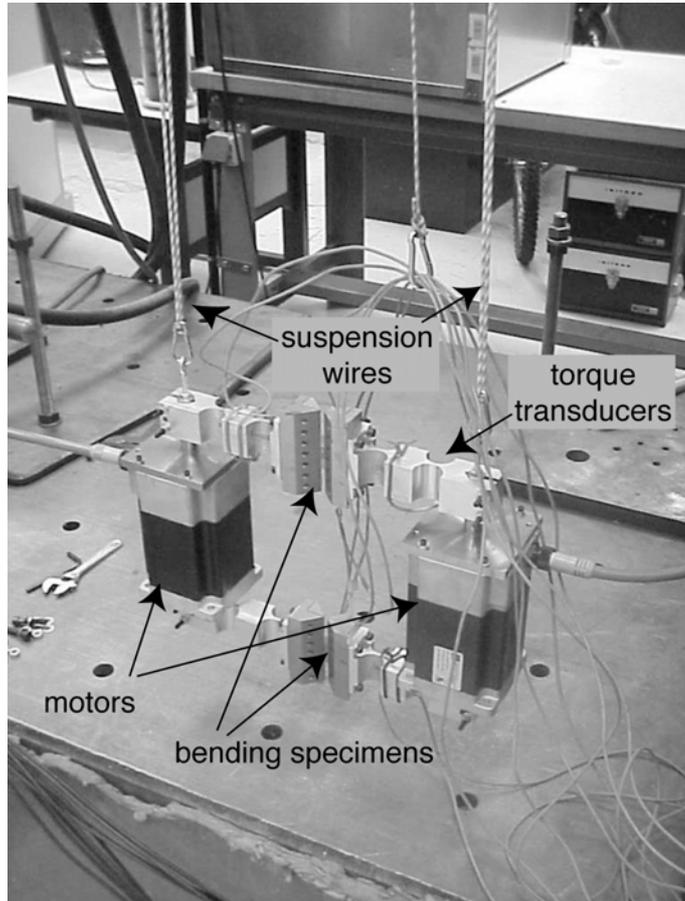


Fig. 2a. Machine in initial configuration (0°).

2 PRINCIPLE AND DESCRIPTION

The machine uses 2 identical specimens. The heads of each specimen are fixed with grips on arms that are attached to the shaft or the stator of a step motor. Each aluminium arm consists in 2 torque transducers

that are equipped with strain gauges. Combinations of the bending moments measured with the 8 transducers can be used to verify the pure bending state (see section 3.1).

The machine is angle-controlled by the two step motors. A program developed in Labview environment controls the step-motors and records the measurements.

Figure 2 illustrates the machine just after the setting-up of the specimens ($\alpha = 0^\circ$) and after symmetric bending of the 2 specimens up to $\alpha = 90^\circ$.

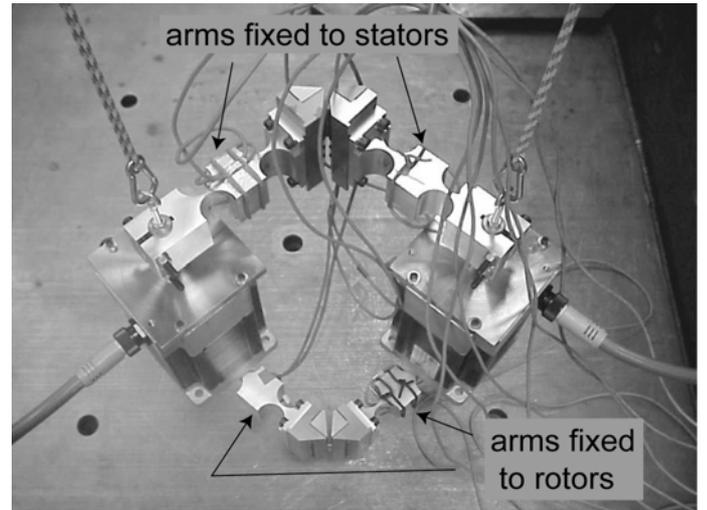


Fig. 2b. Machine after bending to 90°.

3 MEASUREMENTS AND VALIDATION

3.1 Loads evaluation

The bending moment applied to the specimens as well as the spurious loads can be derived from the strain gauges measurements made on the 8 torque transducers.

3.1.a Torque transducers

The bending moment at the centre of each torque transducer can be derived from the tension U measured as the output of an extensometry bridge connected to the 4 gauges so that (see Fig.3):

$$U = K[\varepsilon_{u1} - \varepsilon_{l1} + \varepsilon_{u2} - \varepsilon_{l2}] \quad (1)$$

3.1.b Measurement of spurious forces

It can be noticed from that expression that the transducers are not sensitive to tension and compression. However these measurements made at different points of the machine enable to evaluate

the moment in the specimens as well as the spurious forces.

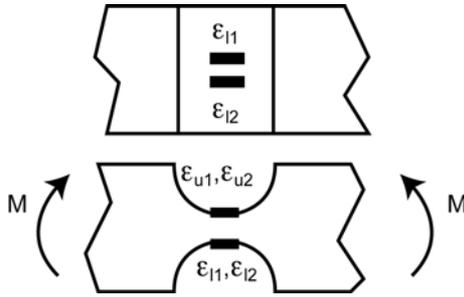


Fig. 3. Torque transducers.

Considering that the beam theory can be applied to the complete machine (motors and attached specimens) considered as a closed arc, the internal forces (generalised stresses) at current point P along the arc can be expressed as :

$$\{F_{int}\}_o = \begin{Bmatrix} X\bar{x} + Y\bar{y} \\ M_o\bar{z} \end{Bmatrix} \text{ with } M_P = M_o + Xy_P - Yx_P \quad (2)$$

\bar{z} being parallel to the axes of the motors.

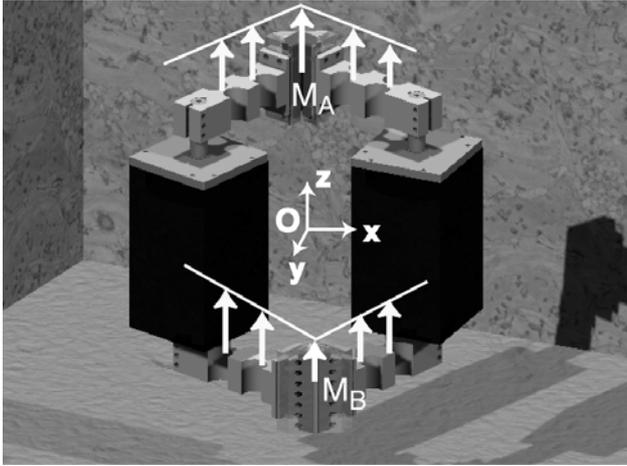


Fig. 4. Moments measured by torque transducers and moments in the specimens.

In practice, moment M can be measured at 8 different locations P_i along the arc i.e. at the centre of each torque transducers (2 per arm, see Fig. 4). The values of X, Y and M_o can be derived from the minimisation of an error function :

$$\text{Min}_{(X,Y,M_o)} [G] \quad \left. \begin{array}{l} \text{with } G = \sum_{i=1:8} \left(M_{P_i}(X, Y, M_o) - M_{P_i}^{exp} \right)^2 \end{array} \right\} \quad (3)$$

Figure 5 illustrates the evolution of the spurious shear X and tension/compression Y forces during a cycle of amplitude $\pm 90^\circ$. The measured shear force X cannot be measured with accuracy for small bending angles where a singularity is observed. For

higher angles, the value of shear force X, as well as tension-compression force Y, is less than 0.01 N. The corresponding stresses are negligible (less than 0.1 MPa) when compared to the tension-compression stresses (a few 100 MPa) due to the applied bending moment (within the range ± 6 Nm for this test). These results validate that the specimens are in pure bending state.

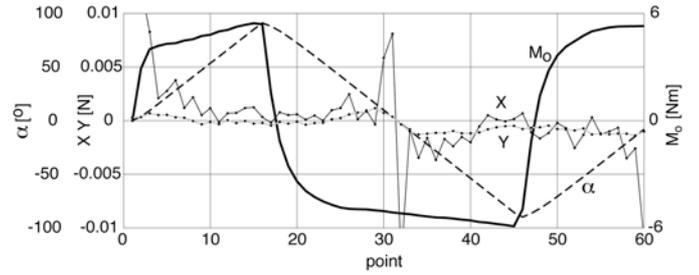


Fig. 5. Measurements of the spurious forces.

3.2 Strain measurements

3.2.a From gauges

Strain gauges can be glued on each side (labelled + or -) of each specimen A and B. The mean value of the surface strain in each specimen can be calculated as:

$$\varepsilon_{surfA} = \frac{\varepsilon_A^+ - \varepsilon_A^-}{2} \quad \varepsilon_{surfB} = \frac{\varepsilon_B^+ - \varepsilon_B^-}{2} \quad (4)$$

In practice, the symmetry of the system allows to consider that the value of the surface strain is equal to the mean value:

$$\varepsilon_{surf} = \frac{\varepsilon_{surfA} + \varepsilon_{surfB}}{2} \quad (5)$$

3.2.b From motor angle

Besides, if the specimens can be assumed in a pure bending state, their deformed state is a circle so that the surface strains can also be deduced from the measurement of the bending angle α by using the following expression :

$$\varepsilon_{surf} = \alpha_{specimen} \frac{t}{2L} \quad (6)$$

The value of angle α can be deduced from the angle applied by the motor according to a correction that takes into account the machine compliance S :

$$\alpha_{specimen} = \alpha_{motor} - S M \quad (7)$$

Both procedures have been used during several experiments on different specimens. The responses

of the gauges as well as the motor angle measurements are plotted on figure 6 for the first elastoplastic cycle of a bending test. The correlation between the values of the angle as deduced from the strain gauges measurements or from the motor angle is good until the rupture of the gauges. Some gauges gave good response for strains with a value up to about 10% but for a limited number of cycles.

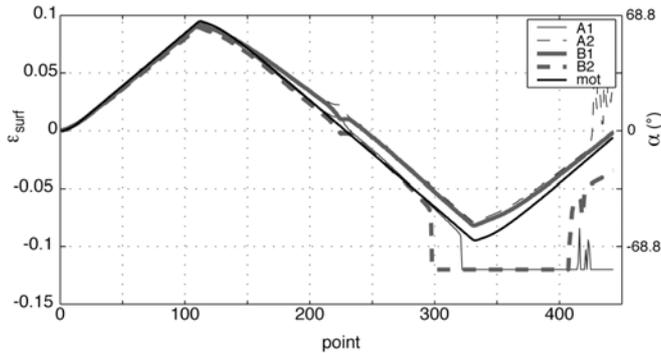


Fig. 6. Strains measurements during a cycle.

These good results first allowed for the calibration of the machine compliance. They also encourage the use of the motor angle measurements to derive the strains: indeed this approach is the only one that can be used for very short specimens on which it is impossible to glue strain gauges.

4 TEST RESULTS

Examples of test results are given for two different metal sheets in figures 7 and 8 where the moment is plotted vs the angle. The first material is a 1 mm thick eutectoid steel sheet. The bending specimens are 6 mm long and 40 mm wide. The identification of its behaviour has been presented in a previous paper [4].

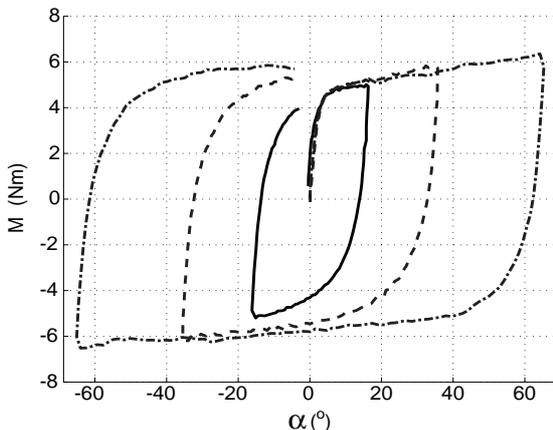


Fig. 7. Experimental bending responses for 3 cyclic tests of different amplitudes on a 1 mm thick eutectoid steel sheet.

The second material is a 0.25 mm thick TRIP steel sheet [5]. The bending specimens are only 2 mm long in order to reach 8% strain and 98 mm wide in order to measure torques that are in the range of the transducers.

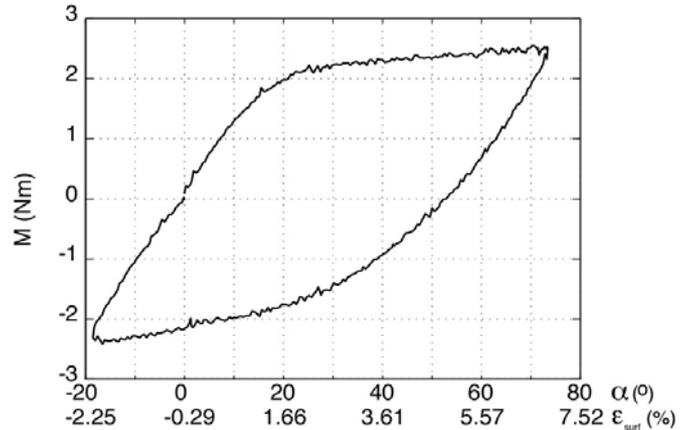


Fig. 8. Experimental bending response on a 0.25 mm thick unstable 301 stainless steel sheet for a cyclic test.

5 CONCLUSION

An original pure bending machine has been built to perform pure bending tests on specimens cut in thin sheets that can be used to identify elasto-plastic models taking into account kinematic hardening. The architecture of the machine has enabled to measure the spurious loads in order to validate that the specimens are in a pure bending state.

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