Determination of the true stress-strain curve for steel sheets, used in cold-drawing machining, by means of experimental tests and Yun Ling theoretical model

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INTRODUCTION

The knowledge of steel sheet mechanical properties is a very significant aim in the manufacturing of industrial components based on cold-drawing machining, where large strains are involved (e.g. in the production of metallic crown caps). In the strain range that covers the region of the stress-strain plot over the necking point, the mechanical behaviour of steel sheets can be described by the Yun Ling constitutive equation, obtained by FEM (Finite Element Method) models calibrated by means of tensile tests on steel sheet samples. The present work describes the experimental activity and the FEM modelling performed at the ENEA Research Laboratories of Faenza to determine the true σ–ε curve of two different types of steel sheets. The described method can so be applied to different types of steel sheets used in cold-drawing machining processes, allowing to estimate their full true σ–ε curves: this type of result can then be inserted in FEM simulations of particular industrial applications.

EXPERIMENTAL TENSILE TESTS: SAMPLES, EXPERIMENTAL APPARATUS AND TESTING PROCEDURE

Two different types of steel sheets (named A and B, respectively) were tested. For each sheet, the samples were cut in direction both parallel and normal to the rolling (indicated by 0° and 90°, respectively). According to the European Standard [1], the dimensions of the samples (Fig. 1) were chosen in order to allow the measurement of the engineering σ–ε curve up to rupture by means of a proper extensometer. Due to their reduced thickness, the samples were gripped by means of the MTS hydraulic system and aluminum tabs (Fig. 2), characterized by a tab bevel angle of about 25°; the sample-tab interface was made by an emery cloth, bonded to the tabs through a cyanoacrylate-type glue. By using the tabs, the sliding of the samples during the tests was avoided; besides, the correct transmission of the load from the grips to the samples was allowed, avoiding in this way dangerous load concentration on the steel sheets.

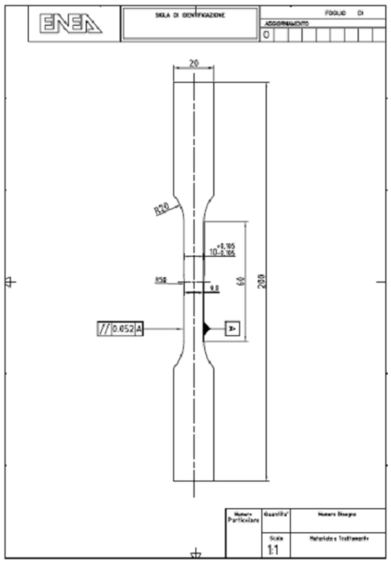

Figure 1: Geometry of the samples.

The electro-hydraulic universal testing machine used is an MTS type, 70 kN load range, equipped with a load cell of 5 kN. For the measurement of the strain up to failure, an MTS extensometer was adopted, with a gage length of 50 mm and a range of 15 mm (from + 12.5 mm to -2.5 mm).
The mechanical characterization of the tested samples, for each type of steel sheet, was performed paying a particular attention to the part of the engineering $\sigma-\varepsilon$ plot over the necking point (extensometer measurements and imaging technique [2] were used while performing the tensile tests, Fig. 3). The tests were performed in displacement-control regime, maintaining a constant strain-speed of about $5 \cdot 10^{-4}$ mm mm^{-1} s^{-1}. On the whole, 32 tensile tests were performed: no. 8 tests on each type of steel sheet. Both the classical stress-strain parameters and the true $\sigma-\varepsilon$ curve up to the beginning of necking were measured.

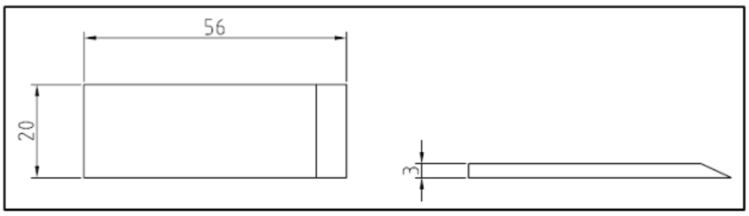

Figure 2: Geometry of the aluminum tabs.

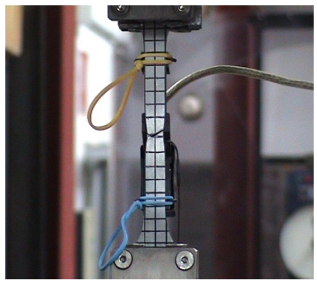

Figure 3: View of the testing system (sample rupture).

TENSILE TEST RESULTS

The data obtained by each tensile test were elaborated and averaged to measure the following parameters [1]: σ_{max} (maximum stress); $\sigma_{0,2\ \%}$ (stress at strain of 0.2 %, stress corresponding to deviation from linearity); E (Young's module); A% (percent elongation at rupture).
A mean $\sigma-\varepsilon$ curve was evaluated averaging all the $\sigma-\varepsilon$ curves obtained for the different types of tested samples (Fig. 4). From these mean curves, the following parameters were calculated:

- $\sigma_{u,eng}$ and $\varepsilon_{u,eng}$: respectively, the maximum engineering stress over the yielding and the corresponding engineering strain. These values (graphically determined on the mean $\sigma-\varepsilon$ curve) detect the point from which the necking starts;
- $\sigma_{u,true}$ and $\varepsilon_{u,true}$: respectively, the maximum true stress and the true strain calculated from $\sigma_{u,eng}$ and $\varepsilon_{u,eng}$ by applying the volume conservation principle.

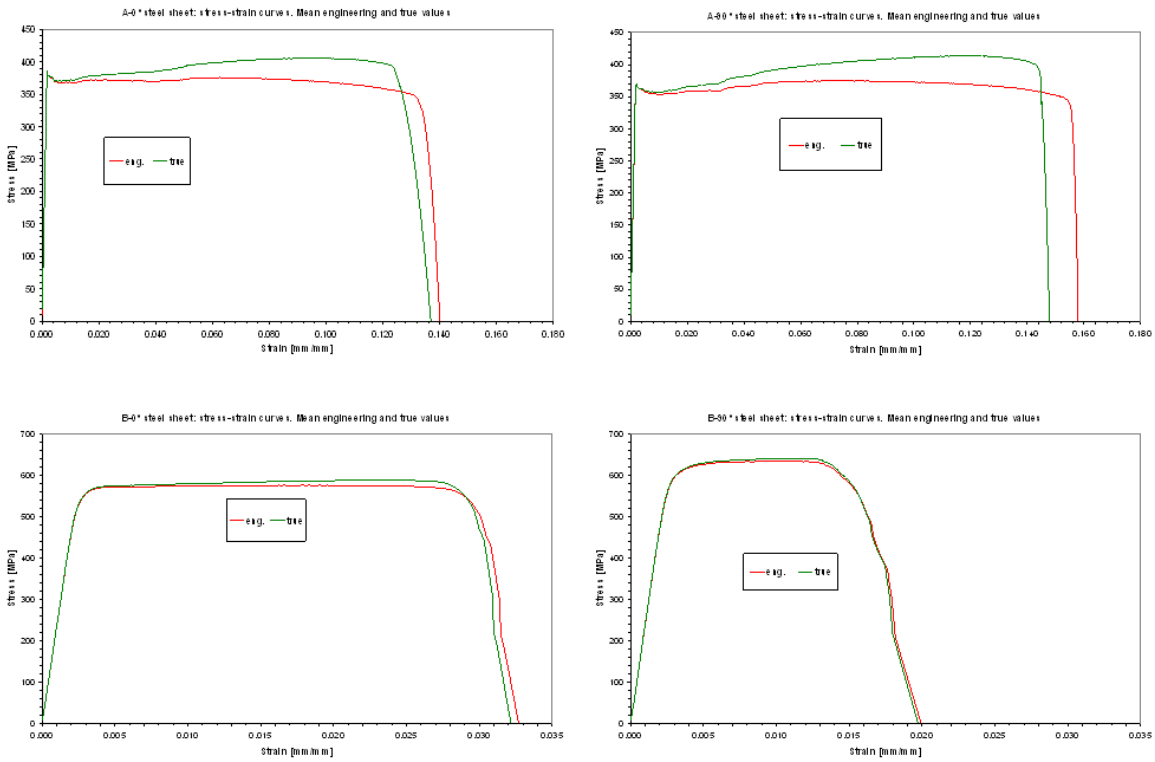

Figure 4: Comparison between engineering and true σ–ε curves

A synthesis of the described parameters is shown in Tab. 1; for each value, a first estimate of the standard uncertainty *u*(*val*) was calculated by means of the following equation:

$$u(val) = \frac{val_{\max} - val_{\min}}{2}$$

steel sheet	σ_{max} [MPa]	$\sigma_{0,2\%}$ [MPa]	A%	E [GPa]	$\sigma_{u,eng}$ [MPa]	$\varepsilon_{u,eng}$ [mm/mm]	$\sigma_{u,true}$ [MPa]	$\varepsilon_{u,true}$ [mm/mm]
A-0°	393 ± 22	374 ± 9	14.76 ± 2.07	228 ± 13	375	0.0656	400	0.0635
A-90°	380 ± 13	362 ± 11	15.95 ± 0.88	210 ± 8	375	0.0747	403	0.0720
B-0°	576 ± 18	572 ± 15	2.37 ± 0.95	233 ± 11	577	0.0183	587	0.0182
B-90°	636 ± 15	626 ± 16	1.02 ± 0.62	235 ± 15	635	0.0102	641	0.0101

Table 1: Mean values of the measured quantities.

THE YUN LING METHOD APPLIED TO THE EXPERIMENTAL DATA: ANALYTICAL MODEL AND FEM RESULTS

Starting from the experimental results, the true σ–ε curve in the field of large strains up to rupture can be obtained by applying the analytical-empirical Yun Ling method [3], described by the following constitutive equation:

$$\sigma_{true} = \sigma_{u,true}\left[w(1+\varepsilon_{true} - \varepsilon_{u,true}) + (1-w)\left(\frac{\varepsilon_{true}^{\varepsilon_{u,true}}}{\varepsilon_{u,true}^{\varepsilon_{u,true}}} \right) \right]$$

The method is based on the simulation of the tensile tests by means of FEM analysis and calculations in the elastoplastic range characterized by large strains. The empirical Yun Ling constitutive equation parameter *w* can be determined through iterative calculations aimed to obtain the best fit between the FEM Load-Extension curve and the experimental one: as a final result of FEM analysis, the true stress-strain curve from the beginning of necking up to rupture can then be calculated.

As a first approach, this analytical model was developed on the experimental results associated to the sample no. 1 of A-0° steel ($\sigma_{u,true}$ = 396 MPa and $\varepsilon_{u,true}$ = 0.059 mm/mm). The whole FEM analysis started from the experimental true $\sigma-\varepsilon$ curve, properly resampled, and from the measured value E = 223 GPa (Poisson's ratio assumed equal to 0.3). Taking advantage of the sample axial symmetry, simplified models were used, focusing FEM analysis both on the part subjected to tensile stress and on the part instrumented by the extensometer (Fig. 5). Then, the FEM analysis was performed by using elements of PLANE and SOLID type. The experimental and calculated load-extension curves were proved to converge in both the cases of PLANE and SOLID elements: the convergence was reached when the value of the *w* parameter is 0.72 (as an example, some results of FEM analysis, in the case of PLANE element, are shown in Fig. 6-7-8-9). Nowadays, FEM analysis is going to be extended to the mean true $\sigma-\varepsilon$ curves obtained for A-0°, A-90°, B-0° and B-90° steel sheets.

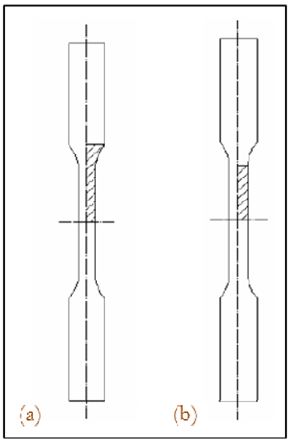

Figure 5: Simplified model for the sample: a) part subjected to tensile stress b) part instrumented by the extensometer.

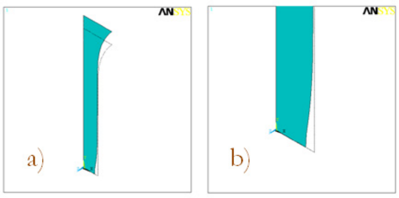

Figure 6: Final shape of the examined parts a) and b) of the sample under the action of the tensile stress.

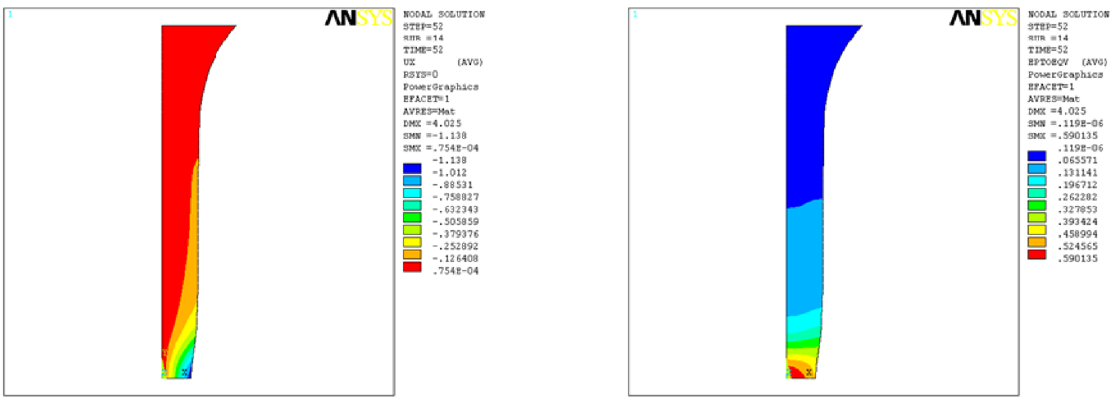

Figure 7: Distribution of transversal displacements (left image) and strain (right image) on the examined part a).

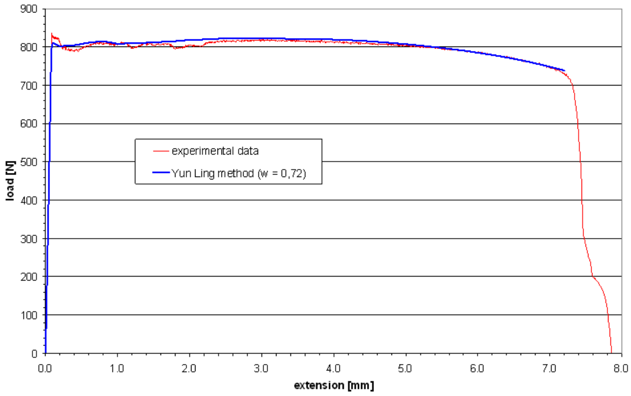

Figure 8: Calibration of the Yun Ling method vs. experimental data in terms of load-extension curves.

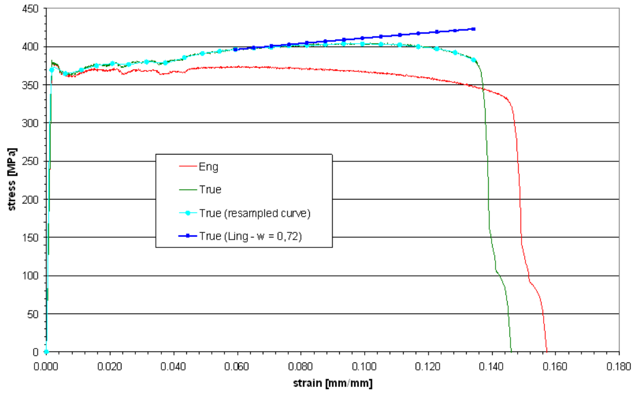

Figure 9: Comparison among Yun Ling method and experimental data in terms of stress-strain curves.

CONCLUSIONS

The experimental tensile tests gave good results for what concerns the sample ruptures, that were all inside the length of the reduced section of each sample; the type A material was proved to be more ductile than type B. The measured mechanical parameters showed values characterized by a reduced dispersion.

For what concerns the implementation of the Yun Ling analytical model, a first attempt based on the result of a single sample showed the goodness of the model itself. In particular the same analytical model, based on the mean true $\sigma-\varepsilon$ curves, can be used to determine the mean mechanical properties of different type of steel sheets; these tests are now developing at ENEA laboratories.

REFERENCES

[1] UNI EN 10002-1: Metallic materials - Tensile testing - Part 1: Method of test at ambient temperature.
[2] I. Scheider, W. Brocks, A Cornec, Journal of Engineering Materials and Technology, 126 (2004).
[3] Yun Ling - AMP Journ. of Tech., 5 (1996).