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Uniaxial Near Plane Strain Tensile Tests Applied to the Determination of the FLC_0 Formabillity Parameter

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An alternative procedure for the determination of the FLC_0 value, the limit strain value corresponding to the plane strain mode of the Forming Limit Curves (FLC), a critical parameter in the sheet formability analysis, is suggested and compared with conventional Nakazima simulation tests. The procedure was tested using two different materials: interstitial-free quality steel (IF) and a spheroidized SAE 1050 steel. The intrinsic tensile test, in a near plane strain state, was performed using a small number of samples, with dimensions suggested by the literature. The results were checked against Nakazima test results using the same materials. The plane strain test was reliable in determining consistent FLC_0 values and should be preferred since it is not affected by the geometric aspects and by friction, which do affect the Nakazima test. The reliability of the FLC_0 values obtained by near plane strain was also corroborated through comparison with literature data.

Keywords: *deep drawing, Forming Limit Curve, sheet metal forming, plane strain deformation*

1. Introduction

The last decade saw an increasing interest in the understanding of the physical metallurgy associated with the evolution (during straining) of both microstructure (damage accumulation/microvoids evolution) and crystallographic texture, aiming at locating the yield point and, consequently, ductile fracture during sheet metal drawing[1,2]. This interest relies on the support of true stress - true strain curves, on using alternative flow criteria (quadratic and non-quadratic) and on using Forming Limit Curves FLCs, i.e., on characteristics of the material to be drawn.

These Forming Limit Curves (FLCs) introduced by Lankford (1947), Keeler and Backofen and Goodwin[3-5], allow a comprehensive representation of sheet formability and have been widely used as a criterion in the optimization of the drawing process and as an aid in die designing[2,5-7].

The Nakazima simulation test (1968) has been commonly applied for the evaluation of the FLCs. This test is sensitive to the sheet thickness, surface conditions, lubricants, tool type and geometry[2,5], besides influences inherent to the test itself, since the sample does not remain flat, but is increasingly curved during straining (i.e. the strain path is not entirely contained in the sheet plane)[8]. Further, it should be added that obtaining the FLC curves via Nakazima is time consuming and expensive, as it requires the preparation and testing of several samples of different geometries and dimensions. The minimum recommended number of samples from the industrial practice is 30 samples. A typical setup consists of three replicas of each of the following dimension, in RD-(rolling direction-mm) × TD-(transverse direction-mm): 50 × 220; 80 × 220; 100 × 220; 110 × 220; 120 × 220; 130 × 220; 140 × 220; 160 × 220; 175 × 220; 220 × 220[†**].

The methodology used in determining the FLC curves is based on the analysis of the deformation of sheet samples, which contains a circle grid printed over its surface. The samples are deformed in different conditions, in order to simulate different strain paths to which an actual part would be submitted during forming. The results of all sorts of tests designed for such purpose, being either intrinsic or simulated (regardless of friction) , consists in measuring the ellipses (i.e. the deformed circles of the printed circle grid) near the fracture region, calculating the largest principal strain (ε_1) and smallest principal strain (ε_2) in the sheet plane[5,9-11]. A plot of these points generates V-type curves, which allow defining the boundary of conformational limits of that sheet (ASTM E2218, ISO 12004-2:2008)[12, 13] .This point is where local thinning starts (reduction of resisting section) and that, at the end, culminates with fracture (generating the fracture limit curves, FrLC).

The apparent transferability of the concept of the FLC is tempting, but it is known that the strain path (which is not always a straight line) in formed parts influences the position of the FLC[9,10,14,15]. This path can be described by the strain ratio $\beta = \varepsilon_2/\varepsilon_1$. A path corresponding to biaxial tension (stretching) occurs for $\beta \sim 1$. A path close to plane

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strain is associated with ε_2~0 (equivalent to β=0). A path corresponding to deep drawing situations find values in the region -1<β<-0.5[7]. Studies conducted in several types of automobile parts[5,15,16] show that over 80% of formed pieces usually fail under conditions of near plane strain (β~0), which is also the minimum of the obtained FLCs.

This propensity for failure under near plane strain conditions and the previously mentioned disadvantages of the Nakazima test[17] brought out the intrinsic tensile test under the condition of plastic deformation near to the plane strain[5,15,16] condition. In this case, the full determination of the FLC is avoided and all analysis is based on the FLC_0 point, which corresponds to the minimum (lowest point) of the FLC curve under plane strain, i.e., for the condition for which the smallest principal strain in the plane of the sheet vanishes: $\varepsilon_2 \rightarrow 0$.

The objective of this work is to evaluate the possibility of replacing Nakazima tests by a fast and safe determination of the FLC_0 value through tensile tests that will lead to near plane strain deformation, using a smaller number of samples.

2. Material and Methods

2.1. *Material*

Two kinds of blanks were used in the present work: a 0.75 mm thick Interstitial Free (IF) steel sheet and a 1.48 mm thick spheroidized SAE 1050 carbon steel sheet. Chemical compositions, as furnished by the suppliers, and mechanical properties (according to ABNT NBR 16284; ASTM E 517) [18,19] are given, respectively, in Tables 1 and 2. The first steel is ductile and widely used in drawing industries, especially by automobile manufacturers and by home appliance industries, while the latter has higher mechanical strength, which usually impairs formability. The microstructure (ferrite matrix containing spheroidal cementite) somewhat decreases this drawback and the steel is mainly used in applications such as toecaps for safety boots.

Steel formability may be evaluated by a series of mechanical properties, derived from a conventional tensile test, these are: yield stress (σ_y), ultimate tensile stress (UTS), elongation for a gauge length of 80 mm (ε_f), plastic anisotropy ratio (r_α, where α refers to the angle between rolling direction and tensile sample loading direction) and the parameters of Hollomon's equation, defined by

$$\sigma = K\varepsilon^n \tag{1}$$

The values of these parameters for both steels, provided by the supplier, are given in Table 2.

2.2. *Samples and testing methods*

The geometries of the samples used specifically for plane strain (tensile) tests are shown in Figure 1. The dimensions were based on Wagoner's previous studies[20].

The technique called *serigraphy* was used for recording a set of circles on the metallic samples. It is a simple process which provides good sharpness for measurements of the circles. It relies on the transfer of drawings onto serigraphy chromes and from them onto the metal sheet surfaces, via ink tanks.

Table 1. Analyzed composition of the investigated steels.

Steel	IF	SAE 1050
wt.%C	0.0015	0.4980
wt.%Si	0	0.1700
wt.%Mn	0.1170	0.6400
wt.%P	0.0100	0.0190
wt.%S	0.0072	0.0020
wt.%Al	0.0320	0.0102
wt.%Ti	0.0530	-

Table 2. Base mechanical properties of the investigated steels.

Steel	IF	SAE 1050
σ_y [MPa]	178	333.4
UTS [MPa]	336	490
ε_f [%]	42.1	24.4
r_0	1.73	1.01
r_{45}	1.23	0.71
r_{90}	2.02	0.87
K [MPa]	584	803
n	0.22	0.18

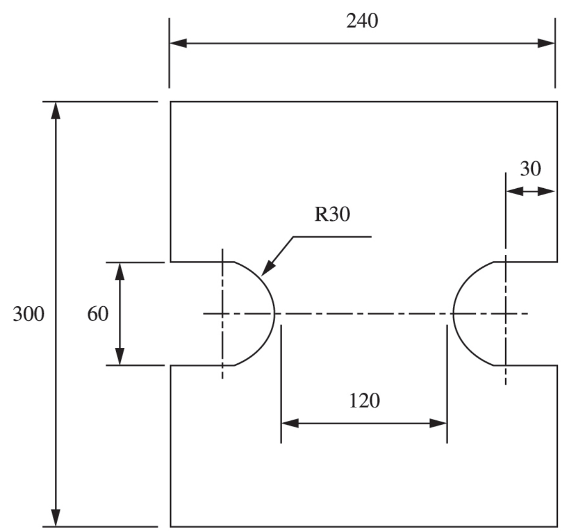

Figure 1. Sample geometry, used in the uniaxial tensile tests.

The sequential steps of serigraphy refer to the production of the chrome; choice of the serigraphy tissue; preparation of frames (degreasing, drying, emulsification, drying, additional emulsification, drying, exposure to ultraviolet light; development; drying) and applying ink onto the surface.

The methodology used for the tensile tests under condition of plastic near plane strain, was the following:

- Pre-recording of a net of circles of d_0 = 2 mm on the sample surface;
- Loading of the samples, leading them to necking/

rupture through uniaxial tension. Three samples were used for each condition, with the major axis parallel either to the rolling direction (RD) of the original sheet or to the transverse (TD) direction;
- Measurement of the ellipses along the longitudinal axis of the plastically deformed samples, adjacent to the necking region, for the determination of the major and minor axes, d_1 and d_2, respectively, using an image analysis system (CAMSYS). Six ellipses were measured, three to the left and three to the right of the center line in the necked region. This system allows the automated reading of major and minor axes (d_1 and d_2) in the ellipses close to the thinning area. From these values, the true principal strains are calculated through:

$$\varepsilon_{1,2} = \ln\left(\frac{d_{1,2}}{d_0}\right) \quad (2)$$

The assessment of FLC_0 values resulting from the unidirectional near plane strain plastic deformation is obtained by comparing results of the same parameter arising from a full determination of the respective FLCs using the Nakazima test, performed in the present work. Results are reported as true (i.e., not engineering) strains, according to Equation 2.

The equipment used for determining the FLC_0 values in near plane strain (tensile test) are briefly described below:

- Projector of vertical profile: Objective lenses 10, 20, 50 and 100x and digital reader with geometric processor;
- Universal Testing Machine with maximum capacity 600 kN electromechanical drive and speed ranging from 0.01 to 300 mm/min. The tests were conducted under displacement control;
- Wire electro-erosion machine: to obtain low roughness in the cut face, hence preventing crack nucleation at this site during tensile testing.

The Nakazima simulation tests[21] were carried out in a Erichsen press, with a 100mm-diameter punch. Sample sizes for the IF steel were 220 × 50, 220 × 80, 220 × 100, 220 × 110, 220 × 120, 220 × 130, 220 × 140, 220 × 160, 220 × 175 and 220 × 220 mm and 0.75 mm thickness. In the case of the AISI 1050, the same sample sizes were tested, but the samples with width smaller than 140 mm invariably broke in the blank holder, therefore results for this steel will be limited to 220 × 140, 220 × 160, 220 × 175 and 220 × 220 mm samples, with thickness 1.48 mm. Both steels were investigated in the RD configuration only.

3. Results and Discussion

The critical strains for necking of the samples subject to Nakazima's test are presented in Table 3. Each value represents the average of a large number of circles (also given in the table) and the standard deviation of the measurements is represented in parenthesis (referring to the value's last digit). As expected, the IF steel presents superior drawability when compared to the AISI 1050 steel. Based on these results, the coordinates of FLC_0 can be derived following the ASTM E2218 standard[12], corresponding, respectively, to (0.52, 0.00) and (0.42, 0.00) for the IF and the 1050 steels. Although the result is compatible with the lower formability of the 1050 steel, analysis of the base properties of both steels (Table 2) would imply a worse behavior, suggesting that the FLC_0 parameter, derived from Nakazima's test, is overestimated (at least for the 1050 steel).

The results of the near plane strain tests are shown in Figure 2, together with the ones obtained from the Nakazima's tests for both steels. As observed, the values of the near plane strain test are smaller than those expected from the traditional FLC curve. As discussed before, this outcome is expected, since Nakazima's test is affected by friction and geometric factors related with the interaction between punch and the specimen.

The issue of the influence of geometrical and friction factors in the determination of Forming Limit Curves has been addressed already by several authors[17,22]. Charpentier, for example, showed, that samples deformed under curvilinear deformation paths (off the stretching plane) presented higher limit strains as compared with true biaxial tests under the same conditions[22].

The discrepancy is more severe for the case of the AISI 1050 steel. As already discussed, the base properties of this steel suggest a poor formability, which is reproduced in the

Table 3. Results from Nakazima's test. Limit strains are reported as true plastic strains (Equation 2) and were defined by measuring the ellipses adjacent to localized necking.

Width [mm]	IF Steel			AISI 1050		
	Points	ε1	ε2	Points	ε1	ε2
220	108	0.80(2)	0.11(1)	64	0.72(1)	0.17(1)
175	97	0.68(1)	0.12(1)	93	0.69(1)	0.20(1)
160	66	0.59(2)	0.04(1)	67	0.77(1)	0.14(1)
140	81	0.64(1)	–0.01(1)	92	0.52(2)	0.04(2)
130	113	0.70(1)	–0.08(1)	---	---	---
120	88	0.94(1)	–0.15(1)	---	---	---
110	114	1.03(1)	–0.19(1)	---	---	---
100	99	1.07(1)	–0.23(1)	---	---	---
80	67	1.10(1)	–0.26(1)	---	---	---
50	88	1.20(1)	–0.28(1)	---	---	---

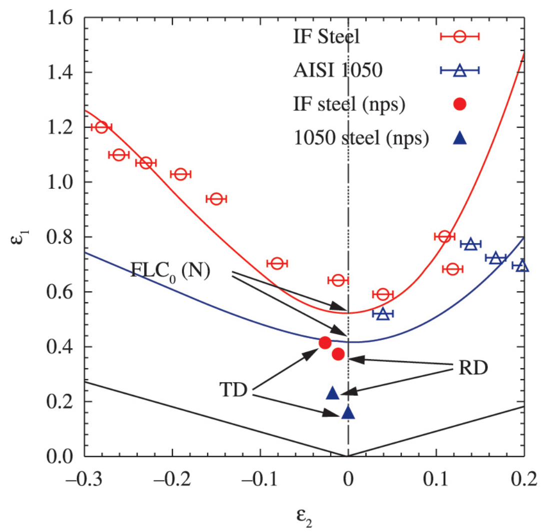

Figure 2. Results from the Near Plane Strain tests (nps), solid symbols, compared with the traditional Nakazima's test (N) results (empty symbols). The estimated FLC_0 value for Nakazima's test is indicated for both steels. The lines are drawn just as a guide to the eye.

near plane strain tests. The evaluation of the forming limit curve, however limited, points out to a somewhat similar formability compared with the IF steel. The FLC_0 parameter is known to increase when sheet thickness increases[16]. Thus, in principle, the formability of the spheroidized SAE 1050 medium carbon steel could be made similar to that of an IF steel, by selecting the appropriate sheet thickness. In this instance, taking the larger thickness of the AISI 1050 steel as basis, one could assume that the formability of both sheets would be approximated, justifying the results of the Nakazima's test. The results of the near plane strain test indicate, however, that this hypothesis is questionable.

The results for the IF steel are consistent with published data on similar steels[23]. The near plane strain data are also smaller than the FLC_0 value derived from Nakazima's tests, but in this case the difference is smaller compared with the case of the AISI 1050 steel. These results are consistent with the ones obtained by Freitas et al.[24] in a hot-dip galvanized IF steel, which were based on the conventional FLC determination (using Marciniak's test). These authors report a high susceptibility of the test to the lubrication conditions.

We may also compare the obtained FLC_0 (as an engineering strain) values with the ones predicted using an empirical relation derived by Keeler and Brazier[25]:

$$FLC_0 = (0.233 + 0.143t)(n / 0.21) \tag{3}$$

where t is the thickness, in mm, and n, the strain hardening exponent. Using the previously reported values for these parameters and converting to true plastic strains, this equation predicts FLC_0 to be $\varepsilon_1 = 0.297$ for the IF steel and 0.347 for the 1050 steel. The results for the IF steel is consistent with the one determined in the near plane strain test (the small difference may be a result in using different strain rates for the test), and shows, again that the Nakazima's test value overestimates the limit strain. In the case of the 1050 steel, the predicted value is much higher than the one determined using the nearplane strain test, butthis is expected, since Equation 3 was derived for microalloyed steels. The presence of cementite in the microstructure surely increases the propensity to necking comparedto a single phase ferritic matrix.

Finally, the comparison between the near plane strain results obtained from samples extracted along RD and TD show differences, but no trend can be identified, at least for these two steels. These differences will be further explored in a forthcoming work.

4. Conclusions

The results obtained in the present work allow drawing the following conclusions:

- The plane strain test showed to be suitable for determining the value of the FLC_0 and it is performed with a smaller number of samples than that required by the Nakazima method, i.e., 6 samples are required (3 samples for the RD direction and 3 samples for the TD direction) in the plane strain test, while at least 30 samples are required in the Nakazima test for the full determination of a FLC (from which FLC_0 is derived);
- The results obtained in the near plane strain tests are consistently smaller than the FLC_0 values derived from Nakazima's tests, which are performed out of plane and in contact with a punch, hence influenced by friction and by a non-plane deformation path. Since the near plane strain tests are not influenced by these factors, their results are believed to be more representative of the reality;
- Anisotropy of the sheet positively influences the critical strain for necking in the near plane strain tests, however, based only on the two steels investigated in the present work, no trend could be identified.

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