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Determining the fracture forming limits in sheet metal forming: A technical note

Valentino AM Cristino[1], Maria Beatriz Silva[2], Pak Kin Wong[1] and Paulo AF Martins[2]

Abstract
This technical note describes an experimental method to determine the formability limits by fracture in sheet metal forming. The method makes use of laboratory test specimens commonly utilized in the mechanical, fracture and formability characterization of sheet materials and involves determination of the gauge length strains at the cracked regions of the specimens after testing. The presentation explains how measurements are made and what calculations need to be performed in order to determine the fracture forming limit by tension in the principal strain space. The method is applied to Titanium grade 1 sheets, and the fracture forming limit is validated by subsequent experiments with single point incremental forming.

Keywords
Experimental method, sheet metal forming, fracture forming limits, gauge length strains

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Introduction

In a recent paper, Isik et al.[1] proposed a new understanding on the fracture forming limits by tension (FFL) and by in-plane shear in sheet metal forming. The FFL is schematically plotted in the principal strain space as a straight line falling from left to right with slope equal to "−1" (Figure 1(a))

$$\varepsilon_1 + \varepsilon_2 = -C \tag{1}$$

In the equation above, C is the critical through-thickness strain $\varepsilon_{3f} = \ln(1 - R_f)$ at fracture, and $R_f = (t_f - t_0)/t_0$ is the limiting reduction in thickness, where t_0 is the initial thickness, and t_f is the thickness at fracture.

Subsequently, Martins et al.[2] showed that the fracture locus given by equation (1) can be written as

$$D_{crit} = \frac{(1 + r)}{3}[\varepsilon_1 + \varepsilon_2] \tag{2}$$

where r is the anisotropy coefficient, and D_{crit} is the critical value of the ductile damage according to the non-coupled void growth damage-based criterion due to McClintock.[3] Martins et al.[2] also showed that equation (2) should include an extra term and be rewritten as

$$D_{crit} = \frac{(1 + r)}{3}[\varepsilon_1 + \varepsilon_2 - (1 + \beta)\varepsilon_0] \text{ with } \beta = \frac{d\varepsilon_2}{d\varepsilon_1} \tag{3}$$

in case of materials in which the accumulation of damage only starts after a threshold strain ε_0. In these cases, the FFL will present an upward tail and, therefore, a linear fit is no longer possible. The straight line has to be replaced by a curve.

From what was mentioned above, it is possible to conclude that the influence of the material on the FFL is consubstantiated by changes of the critical damage at fracture, anisotropy and threshold strain values. The process plays no influence in the FFL because ductile damage and fracture toughness are material properties, in contrast to the forming limit curve (FLC) that is not

[1]Department of Electromechanical Engineering, University of Macau, Macau, China
[2]IDMEC, Instituto Superior Tecnico, University of Lisbon, Lisboa, Portugal

Corresponding author:
Paulo AF Martins, IDMEC, Instituto Superior Tecnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal.
Email: pmartins@ist.utl.pt

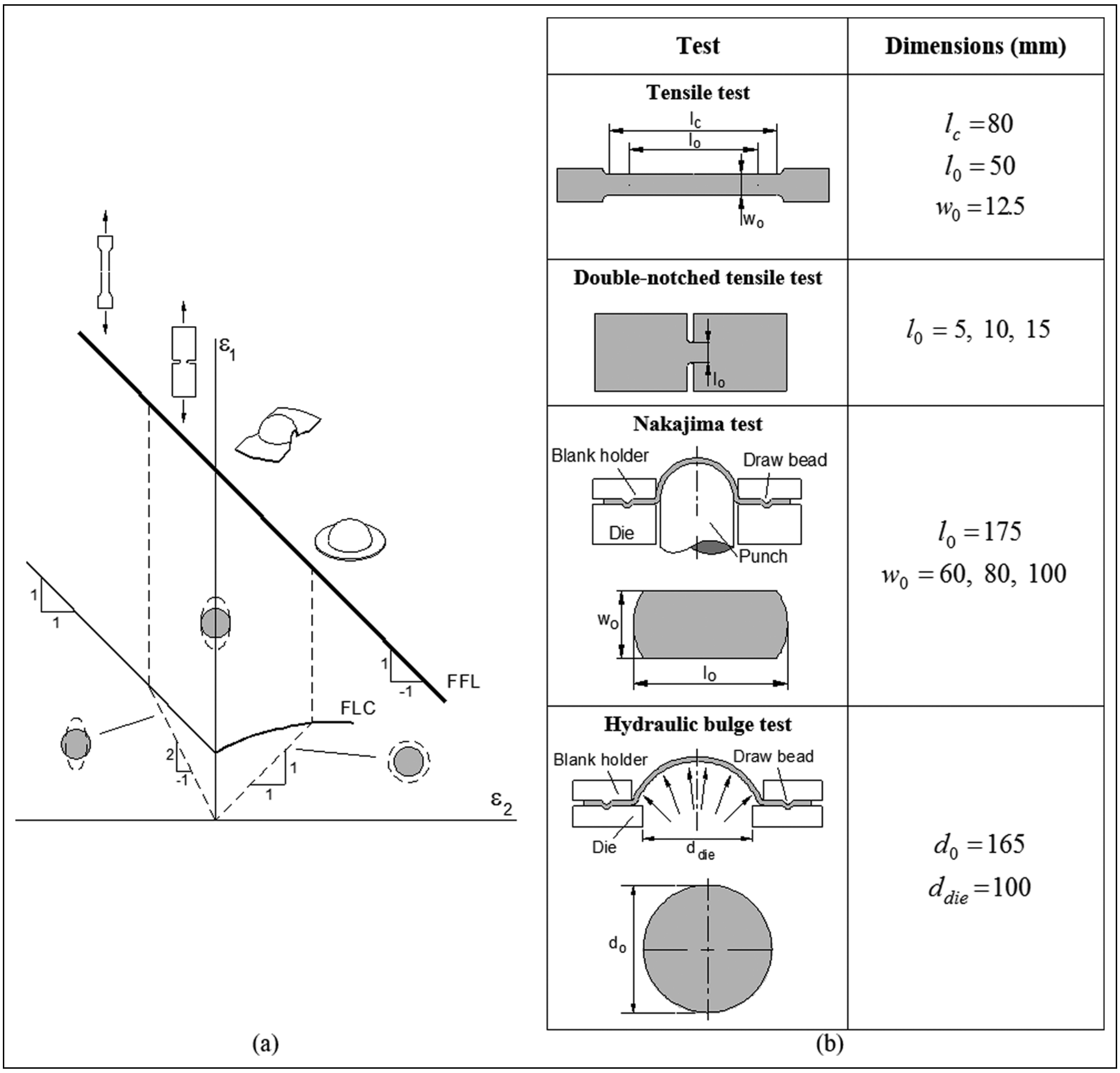

Figure 1. Fracture forming limit by tension (FFL): (a) schematic representation of the FFL in the principal strain space and (b) mechanical, fracture and formability test specimens that were utilized to determine the FFL.

a material property and suffers from strain path dependency.

The phenomenological relation between the FFL, ductile damage, fracture toughness and crack opening by tensile stresses (mode I) is comprehensively discussed by Martins et al.[2]

However, and in contrast to the FLC whose experimental determination method by means of Nakajima or Marciniak formability tests is established in the ISO 12004-2:2008 standard[4] and comprehensively analyzed in the literature,[5,6] the experimental method to obtain the FFL in sheet metal forming is not available in any form of technical standard. The absence of an explicit and commonly accepted set of procedures to determine the FFL in sheet metal forming opens the way for doubts and uncertainties when comparing the fracture strains obtained from different researchers.

Under these circumstances, the main objective of this technical note is to present an experimental method to determine the fracture forming limits in sheet metal forming. The presentation includes a description of how and where measurements should be made, plus the rationale for calculating the "gauge length" strains (hereafter designated as the "fracture strains") at the cracked regions of the specimens after testing.

The presentation is focused on the FFL (mode I), but the proposed method can also be utilized to determine the fracture forming limit by in-plane shear (mode II), which was not considered in the presentation. In fact, as recently showed by Martins et al.,[2] the onset of fracture by in-plane shear is plotted as a straight line falling from right to left with slope equal to " + 1" (that is, perpendicular to the FFL) in the principal strain space.

The presentation includes details of the tension, fracture and formability tests that were utilized by the authors to determine the FFL, and the results of these tests are subsequently validated by means of

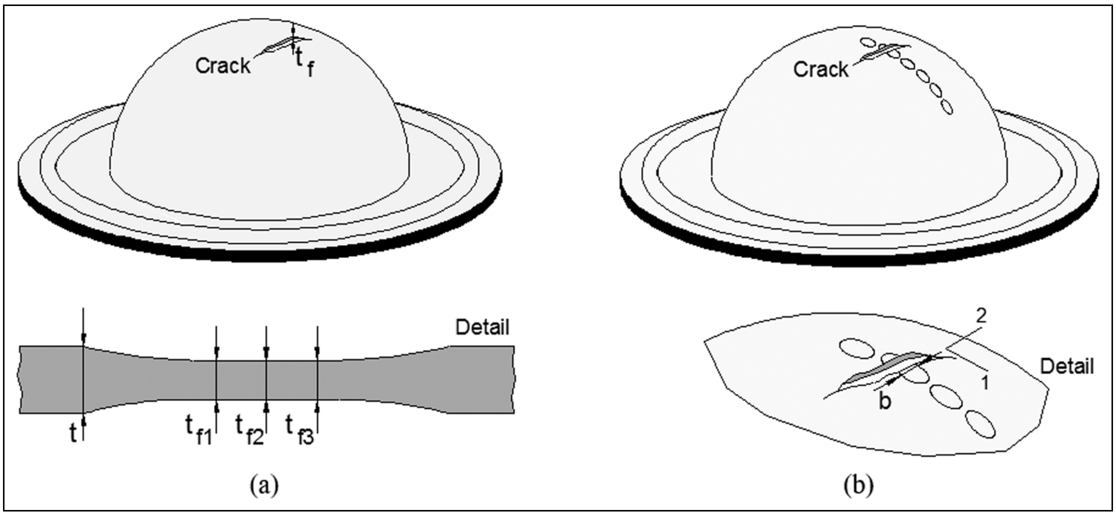

Figure 2. Technique for determining the fracture strains in sheet test specimens: (a) schematic representation of the locations for measuring the sheet thickness t_f along the crack and (b) schematic representation of the minor axis b of the ellipse on the cracked surface of the specimen.

independent tests performed with single point incremental forming (SPIF).

Method

The determination of the fracture forming limit requires cutting out test specimens with different geometries from the supplied sheets and subjected to diverse loading conditions in order to obtain strain loading paths spanning across the principal strain space. Figure 1(b) presents the geometry of the specimens retrieved from mechanical, fracture and formability characterization tests that were utilized by the authors to determine the FFL. Other geometries and loading conditions can be utilized.

The preparation of the specimens involved electrochemical etching a grid of circles with initial diameter d on its surfaces before testing. The correct voltage, current (alternating current (AC)/direct current (DC)), electrolyte and neutralizer to be utilized by the marking equipment depend on the sheet material to be used.

In contrast to the FLC, the FFL cannot be directly obtained from in-plane strain measurements of the grid of circles because even very small circles placed in the neighborhood of the cracks will always provide values that cannot be considered the fracture strains. This is the reason why specimens must be cut along the crack in order to measure the sheet thickness at fracture t_f and obtain the fracture strain ε_{3f} in the thickness direction. This is also the reason why the resulting strains are denoted as the "gauge length" fracture strains.

The sheet thickness at fracture t_f is obtained from the average value $t_f = \sum_{i=1}^{n_m} t_{fi}/n_m$ of a number n_m of individual t_{fi} measurements performed along the crack with an optical microscope equipped with a digital camera with a precision of ± 0.0001 mm. The procedure is schematically shown in Figure 2(a), and ε_{3f} is calculated as follows

$$\varepsilon_{3f} = \ln\left(\frac{t_f}{t_0}\right) \tag{4}$$

The corresponding fracture strain ε_{2f} on the surface of the specimen is calculated after measuring the minor axis b of the ellipse that resulted from plastic deformation and fracture of the circle during the test (Figure 2(b))

$$\varepsilon_{2f} = \ln\left(\frac{b}{d}\right) \tag{5}$$

Finally, the remaining fracture strain ε_{1f} on the surface is obtained by incompressibility

$$\varepsilon_{1f} = -\left(\varepsilon_{2f} + \varepsilon_{3f}\right) \tag{6}$$

Results

The method for determining the fracture strains was applied to characterize the FFL of Titanium grade 1 sheets with thickness $t_0 = 0.6$ mm. The fracture tests were performed with the specimens that are included in Figure 1(b) and the surface of each specimen was electrochemically etched with a grid of circles with diameter $d = 2.5$ mm.

Figure 3(a) shows the FFL that was determined by means of the proposed method and procedure to measure and calculate the fracture strains $(\varepsilon_{1f}, \varepsilon_{2f})$ on the surface of each test specimens (refer to the solid markers). The FFL can be approximated by the following straight line

$$\varepsilon_1 + 0.88\varepsilon_2 = 0.96 \tag{7}$$

This line is in good agreement with the theoretical slope "-1" corresponding to a critical reduction R_f in thickness at fracture (equation (1)). The difference between the experimental slope "-0.88" and the

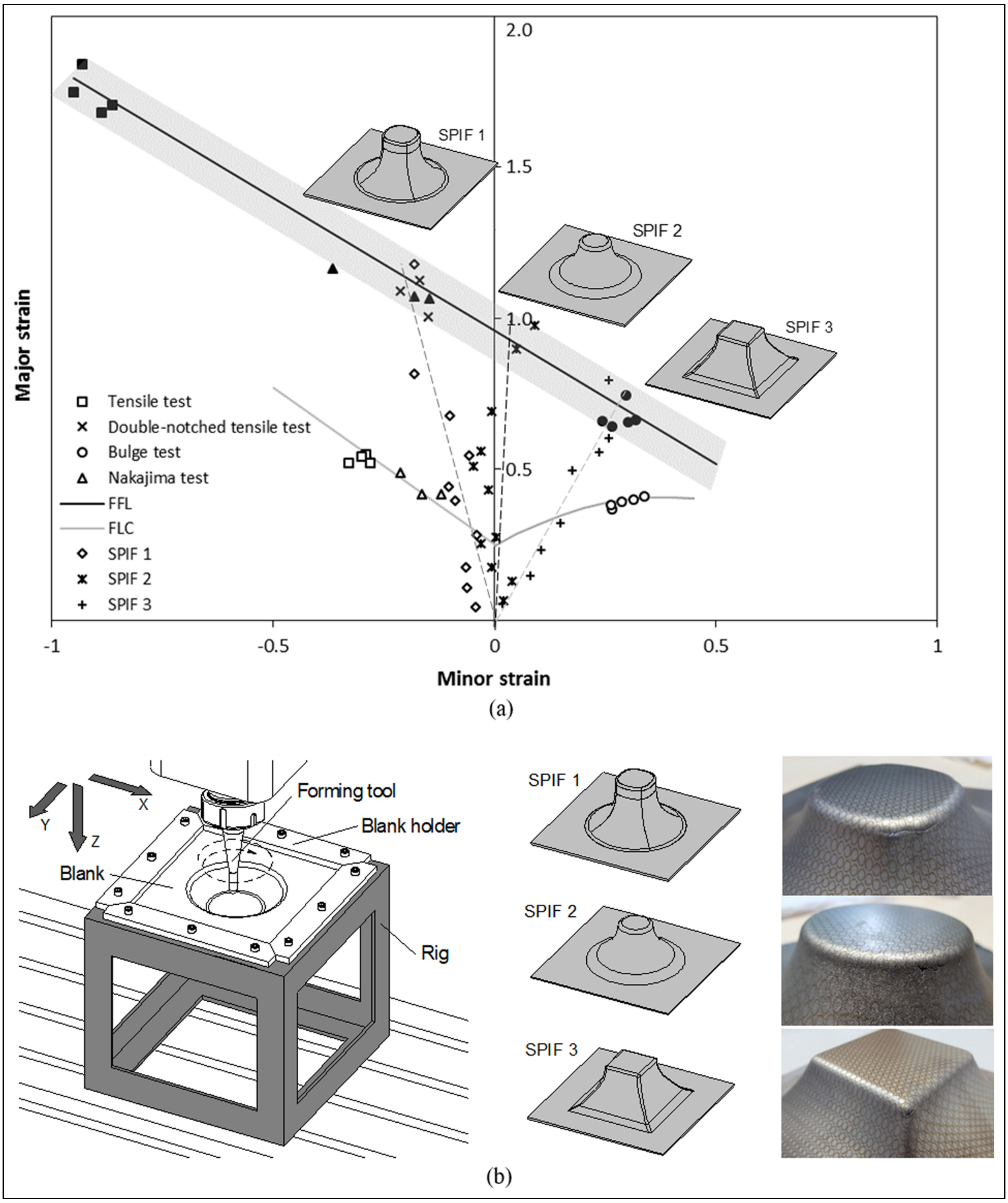

Figure 3. Fracture forming limit (FFL) of Titanium grade 1: (a) determination of the FFL by means of tensile, double-notched tensile, Nakajima and hydraulic bulge tests and validation by means of SPIF tests and (b) truncated with four lobes (SPIF 1), conical (SPIF 2) and pyramidal (SPIF 3) shapes utilized in the single point incremental forming tests with photographs of the cracks.

theoretical slope "−1" is attributed to assumptions in the theoretical model proposed by Martins et al.,[2] namely, the utilization of the non-coupled ductile damage model due to McClintock[3] and the utilization of Hill's plasticity criterion, and also to experimental uncertainties in the determination of the fracture strains.

The open markers in Figure 3(a) correspond to strain pairs at the onset of necking for the specimens that are included in Figure 1(b) and allowed plotting the FLC in the principal strain space for comparison purposes.

Figure 3(a) also includes the strain loading paths obtained from independent tests performed with SPIF. The SPIF tests made use of a hemispherical tip tool with 8-mm diameter and involved truncated with four lobes, conical and pyramidal shapes characterized by stepwise varying angles with the depth (refer to

Figure 3(b)). The geometries of the SPIF tests denoted as 1, 2 and 3 were chosen in order to obtain fracture strains in the tension–compression, plane-strain and bi-axial stretching regions of the principal strain space. The strain loading paths and photographs confirm that SPIF test specimens fail by fracture in crack opening mode I (by tension) without previous necking and that its fracture strains are in good agreement with the FFL previously determined by means of the tensile, double-notched tensile, Nakajima and hydraulic bulge tests.

Conclusion

The proposed method for determining the fracture forming limits in the principal strain space makes use of circle grids that are commonly utilized for obtaining the FLC at the onset of necking. However, instead of making full use of the minor and major axis of the ellipses that result from plastic deformation of the electrochemical etched circles in the necked region of the specimens, the proposed method combines measurements of thickness at fracture and of the minor axis of the corresponding ellipses to obtain the "gauge length" fracture strains.

Application of the proposed method to fracture tests performed with tensile, double-notched tensile, Nakajima and hydraulic bulge specimens made of Titanium grade 1 allowed plotting the FFL in the principal strain space. The FFL of Titanium grade 1 is approximated by a straight line with slope "-0.88" in good agreement with the physical meaning of critical reduction in thickness at fracture. The location of the FFL in the principal strain space was subsequently validated by means of independent tests performed with SPIF.

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