Stakes and solutions for in-plane sheet-metal formability assessment

J Goncalves¹, G Jotz², F Huet³
¹ Global R&D ArcelorMittal Maizières, Voie Romaine, BP30320, 57283 Maizières-lès-Metz Cedex, FRANCE

E-mail: jorge.goncalves@arcelormittal.com

Abstract. In body design, Finite Element Analysis becomes an unavoidable step in optimizing forming processes to ensure the feasibility of a specific designed shape. Different failure criteria exist but the Forming Limit Diagram remains the most used criterion. It can be built in a wide variety of forms but the most usual one is composed only of a Forming Limit Curve (FLC) which represents the onset of localized necking limit of sheet metal. FLC is determined experimentally by standardized Nakajima or Marciniak tests. However, both present lots of roadblocks in the accurate determination of product formability limits due to the use of counter-blanks, no linear strain paths and because they are not adapted for high ductility steels. Tensile tests were performed in the past to determine the left hand side of the FLCs. They were not included into the ISO 12004-2 standard because of technical reasons although they present lots of advantages (frictionless, no curvature effect and planar configuration). Now, thanks to the current advanced technologies and tools, these issues are overcome. In this paper, the advantages of tensile tests compared to Nakajima or Marciniak ones are briefly discussed. The design and conceptualization of specific jaws to perform plane strain tensile tests on AHSS are presented. A wide range of AHSS was characterized through plane strain tensile tests and results were compared to formability limits determined by the usual practice using Nakajima tests. Different evaluation strategies were used to determine the maximum formability: the position dependent method, the time dependent one and close to fracture.

1. Introduction

Forming Limit Diagrams (FLDs) are common used to accelerate the set-up of tools, to detect sources of trouble, to judge the efficiency of tool modifications or new materials and to follow the degradation of tools with time. Keeler / Backofen [1] and Goodwin are the pioneers of FLD introduction. A typical FLD is represented by the major in-plane strain on the vertical axis and the minor in-plane strain on the horizontal axis. One of its key feature is the Forming Limit Curve (FLC) which is defined as a line linking a set of points representing the maximum combinations of plastic strain that a material can withstand in different deformation modes (from uniaxial tension to biaxial tension) before a certain failure criterion. To evaluate the results of simulations and make a feasibility validation, the common used failure criterion for FLCs is the occurrence of localized necking, at a visible level in North America and at the onset (not necessary visible) in Europe.

Two different testing possibilities are defined into the international standard ISO 12004-2 [2] to deform the sample and to determine FLCs. The first one is the well-known Nakajima test – also referred as the hemispherical dome test – with a hemispherical cylindrical punch and the second one is the...
Marciniak test with a flat cylindrical punch [3]. In industrial practices, Nakajima test is the most widely used for different reasons: simplicity, short application time, economy and commercially widespread equipment. It is also considered to approximate the actual automotive stamping conditions, including factors such as testing geometries, bending and unbending and friction conditions. However, from a material characterization point of view, it is not perfect since it influences material behaviour and formability limits. Punch geometry and friction conditions constrained material failure to occur at specific locations in the specimen. They also induce out-of-plane stretching (i.e. increased strain differences between outer and inner fiber) and non-linear strain paths. The initial strain is always bi-axial and gradually the strain path changes towards the final path imposed by the sample geometry and material properties. The lowest point of the FLC, named FLCo, does not coincide anymore with the plane strain axis but it shifts to the right [4]. On the contrary, the other in-plane and totally or almost frictionless methods, like Marciniak test or tensile tests, ensure linear strain paths. The mode of deformation ($E_2/E_1$) kept constant within the plane of the sheet sample and throughout the deformation process. They are more robust and because of these attributes, in-plane forming limits can be more sensitive to material defects and are not influenced to the same extent by tooling geometry variables. However, they do not succeed for different reasons: Marciniak method is more complex in operation. The usual procedure does not often give satisfaction, the selection of appropriate carrier-blind material and hole are very time consuming and critical to the success of the test. Other methods (bulge testing or tensile tests) face some technological issues, like machine capacity and clamping systems, especially with Advanced High Strength Steels (AHSS). Priadi [5] and Holmberg [6] emphasized the advantages and drawbacks of tensile tests for forming limits characterization.

This paper aims at emphasizing the advantages of FLC determination through tensile tests. Specific jaws were designed and conceptualized to ensure the feasibility of plane strain tensile tests on AHSS and new Generation of steels possible. Different evaluation strategies to determine global product Formability limits (like position dependent, time dependent and pre-fracture measurement methods) were investigated to build a new Formability map which should allow a better understanding of the material behavior prior to and during localization and fracturing.

2. Comparison between Nakajima and Marciniak tests
Apart from other discrepancies, the main difference between the two testing methods is the effect of non-proportional strain paths i.e. the pronounced shift to the right of the Nakajima based FLC compared to Marciniak FLCs. The shift to right is due to the Nakajima punch geometry and induced biaxial tension pre-straining [7]. On the contrary, Marciniak tests show a tendency for slightly right curving strain paths. Ghosh [8] found clearly that limit strains are higher in out-of-plane straining than in the case of in-plane straining. Abspoel [4] demonstrates that for a forming grade the bi-axial pre-strain induced by the Nakajima punch geometry is noticeable and for an AHSS it is considerable. However, Sriram [9] and Gutiérrez [10] do not completely share these conclusions and found only negligible differences between both tests. The conclusions of these results have an important implication from an applications standpoint. It is important to validate or not the current practice of using a single FLC to represent a material’s forming capability in regions of complex stampings which encounter varying degrees of in-plane and out-of-plane deformations.

To clarify the difference of FLC level between Nakajima and Marciniak test, FLCo on a 1.2mm CR DP980 and on a 2.9mm HR 980SF were performed according to ISO 12004-2.

It was not possible to get correct trials with the usual procedure of Marciniak i.e. using a carrier-blank with a central hole. Fracture always occurred from the carrier-blank hole (Figure 1). Another methodology was used, hereafter called “modified Marciniak”. It consists on cutting the carrier-blank in two parts and to put them perpendicular to strain direction with a certain gap between them (<1cm). This methodology is accepted by the ISO 12004-2 standard and much more efficient. Failure occurs on expected area and strain paths are in plane strain path and direct. However, it still remains very complex and time consuming. Stretched area is very short due to the small distance between both carrier-blank parts leading the application of FLC analyses methods very complicated.
Modified Marciniak test provides strain path which can be considered as direct. Strain values are slightly lower than with Nakajima tests for the 1.2mm CR DP980 and significantly lower for the 2.9mm HR 980SF (Figure 2). It seems that Nakajima influence is more dependent of steel thickness than strength. With high steel thicknesses, biaxial pre-straining and final formability (strain values) will be.

![Figure 1. Failure of carrier-blank during standard Marciniak trial (left) and success of Modified Marciniak test (right)](image)

Figure 2. Strain paths and ISO values between Nakajima and modified Marciniak FLC0 tests, DP980 (Top), HR 980SF (Bottom)

3. Design of specific jaws
The main roadblock of performing tensile tests for FLC characterization is the tensile machine capacity and an effective clamping system. In order to cover all left hand side of the FLC (from uniaxial to plane strain path), the specimen width has to be modified. The specimen width should be as large as possible to get a condition as close to plane strain as possible in the middle region of the specimen. It is generally assumed that a ratio of 10 must be respected between specimen width and the specimen free length. However, the wider the specimen is, the higher the necessary maximal tensile force and the necessary clamping force are. Most of the time, the maximum possible specimen width is restricted by the testing equipment in terms of the maximum available tensile force, the maximum available clamping force and the grip system. With inappropriate specimen design or insufficient clamping, fracture will not occur at the desired area of the specimen and the expected strain path will not be reached. For plane strain path, the grip system is essential to the success of the trial. The clamping pressure shall be sufficient to avoid sliding. It shall be the closest as possible to the free region and homogeneous or else plane strain conditions will not be satisfied. These conditions are not satisfied by current commercial proposed clamping jaws. Consequently, new ones were specifically designed by ArcelorMittal to be able to perform plane strain tensile tests on AHSS.
3.1. Design of new clamping jaws
ArcelorMittal Maizières is equipped of a 600kN hybrid tensile test machine (with both electro-mechanical and hydraulic drive systems). The original clamping jaws are composed of two double acting hydraulic cylinders and five gripping jaws per clamping jaw. However, they are not satisfactory and plane strain tensile tests impossible on AHSS because of regular failure of the gripping jaws and nonhomogeneous holding pressure. To overcome these issues, a new engineering system of clamping was designed. Instead of using two double acting hydraulic cylinders a system based on 16 single acting hydraulic cylinders (acting on fully independent and free grip wedges) were preferred. Each grip wedges system will absorb specimen waviness and ensure an accurate and homogeneous holding pressure. It ensures the best holding quality.

The stiffness has been also increased and other solutions brought to facilitate the testing operation in fully safe conditions (like specimen holding). Large efforts were made to increase grip wedges efficiency, especially with AHSS, and avoid sliding. The new clamping jaws (Figure 3) allow plane strain tensile tests possible on 300 x 270mm samples.

![Figure 3. Global view of new clamping jaws and grip wedges system](image)

A much better distribution of the applied pressure is now ensured (Figure 4 on 1.2mm CR Fortiform® 1180), and slipping issues have been overcome. To highlight pressure load and distribution, pressure measurement film was used. It allows an accurate control of applied pressure (with 10% of accuracy). When a certain pressure is reached, the film goes to red. The density colour is proportional to the sustained pressure.

![Figure 4. Comparison of holding pressure distribution with pressure measurement films between original clamping system and new one.](image)

4. Experimental procedures
Plane strain condition is the mode of deformation where the material can resist the lowest amount of strain. It is a very unstable condition with a rapid localization. Consequently, the study was focussed on FLC0 characterization by performing tensile tests and comparing them to usual Nakajima tests.

4.1. Materials
Four different AHSS (described in Table 1) were characterized according to different methods FLC ISO 12004-2, FLC time dependent method and close to Fracture.

Table 1. Mechanical properties of tested materials.

| Thickness [mm] | Yield Stress [MPa] | Tensile stress [MPa] | Total Elongation [%] |
|---------------|--------------------|----------------------|----------------------|
| CR Fortiform®1050 | 1.2 | 710 | 1065 | 16.1 |
| CR Fortiform®1180 | 1.2 | 986 | 1242 | 13.8 |
| CR DP780 | 1.2 | 492 | 793 | 19.1 |
| CR DP980 | 1.2 | 669 | 1010 | 13.2 |

4.2. Experimental FLC characterization
Plane strain tensile test were performed with rectangular samples of (270mm x 300mm) without notch. The tensile direction of the specimen is perpendicular to the Rolling Direction of the sheet. A speckle pattern was applied on the specimens for the analysis of the specimen deformation. During testing of the sheet until failure, the evolution of the spotted pattern was recorded thanks to the 5M Aramis® system at a rate of 5 images per second to obtain the deformation history and the values of the true major and minor strains automatically.

As can be seen, there is a clear localization on the middle of the specimen. However, the strain path is not exactly in plane strain condition (chart on the left hand side of Figure 5). A slight shift to the left (ε2 ~ -0.02) is observed but it remains more linear than Nakajima FLD0 trials where a pre-straining in Expansion always occurs. An optimization of the specimen shape should allow to get strain path more centred in plane strain (ε2 ~ 0), by adding for example some notches.

Different evaluation strategies were used to determine the maximum formability: the position dependent method, the time dependent one and close to fracture.
Figure 5. Strain analyses during plane strain tensile test (picture just before fracture), 1.2mm FortiForm® 1050

4.3. Results
For each steel grade, the different limits were compared and plotted on the strain history of the critical point (area where fracture occurs) as shown in Figure 6 and 7. The strain history curves (Figure 7) highlight the progressive failure state of the product. At the beginning one can see the stable nearly homogeneous deformation defined by the nearly linear increase with low slope. Then, a curved area which defines beginning of instability and finally a linear increase with high slope at the end of the curve as fast growth of instable deformation until the crack occurs.

Figure 6. Nakajima and plane strain tensile tests analysed from different methods on FortiForm® 1180 (a.), FortiForm® 1050 (b.), DP780 (c.) and DP980 (d.)
The ISO values are always the first limit reached and they are achieved at the end of the stable area just before the curved area. Time-dependent FLCs are higher than ISO ones ($\Delta<0.05$ in absolute). It has been reported by Huang [11] and the GDDRG [12], that the position dependent method gives rise to consistently conservative FLCs for AHSS. It detects the “beginning of unstable necking” while there might be some small amount of necking might have occurred prior to the necking moment identified by the time dependent method. This is the reason why, position dependent FLCs are most of the time lower.

No significant differences were observed between in-plane and out-of-plane limits as expected due to steels thickness. Depending on the need and practice of OEMs or press shops from different regions, the selection between the two incipient necking criteria can be made.

In terms of perspective, a new Formability map (Figure 8) could be proposed to make a more reliable part feasibility prediction in FEA codes. It would be built from the three forming limits defined earlier (i.e. ISO position dependent, time dependent and pre-fracture) with:

- Area 1: determined by in-plane trials and position dependent method,
- Area 2: between the ISO in-plane FLC and the time dependent out-of-plane one,
- Area 3: between the time dependent out-of-plane FLC and the “Pre-Fracture”,
- Area 4: beyond the “Pre-Fracture” curve.

The way to use these different limits should be defined whatever the steel grade, thickness and local geometry.

5. Summary / Conclusions
Marciniak and mainly Nakajima tests are usually used to determine FLC. Both are recommended by the ISO 12004-2 standard. However, both present a lot of drawbacks. Results are sometimes not
comparable, generally higher with Nakajima tests. They are influenced by the punch geometry (stretching mode is out-of-plane and strain path not direct), friction, high material ductility (sometimes trials are not acceptable because the maximum punch stroke is reached before material failure or fracture occurs on drawbeads or die radius exit). On the contrary, Marciniak test produces in-plane stretching leading to a larger and more uniform deformed area. The usual Marciniak procedure does not give satisfaction. The selection of appropriate carrier-blank material and hole are very time consuming and critical to the success of the test. Another methodology is proposed, called “modified Marciniak”. It consists on cutting the carrier-blank in two parts. It is accepted by the ISO 12004-2 standard and is much more efficient. However, it still remains very complex and time consuming especially for strain analyses. It is important to assess both limits since production stampings experience varying degrees of in-plane and out-of-plane deformation (depending on part and tooling geometry). Tensile tests in plane strain path on large specimen are proposed to determine in-plane formability of sheet metal. A new engineering system of clamping jaws was completely designed to ensure the best holding quality and ensure the success of the trial. It has already proved their efficiency on VHSS. Compared to Nakajima tests, main advantages are the fast and easy determination of product formability limits. Trials are more reliable and results more consistent. They can complete Nakajima results and/or give additional information about product formability.

A new methodology for part feasibility analysis is in sight. It would be based on a new Formability map which would take into account in-plane and out-of-plane sheet-metal formability limits, the position dependent and time dependent methods and pre-fracture values. This new Formability map should be very helpful to define more accurately the different boundaries of part manufacturing success.

References
1. Keeler S and Backhofen W 1964 Plastic instability and fracture in sheet stretched over rigid punches ASM Trans. Q 56:25–48
2. International Standard ISO 12004-2:2008, Metallic materials – Sheet and strip – Determination of forming limit curves – Part 2: Determination of forming limit curves in laboratory
3. Marciniak Z and Kuczynski K 1967 Limit strains in processes of stretching-forming sheet metal Int. J. of Mech. Sci. 9 609-620
4. Abspoel M, Atzema E, Droog J, Khandeparkar T, Scholten M, Schouten F and Vegter H 2011 Inherent influence of strain path in Nakazima FLC testing Int. Conf. IDDRG Spain paper 3.
5. Priadi D, Magny C, Massoni E, Levaillant C and Penazzi L 1992 A new tensile test on notched specimens to assess the forming limit diagram of sheet metals J. Mater. Processing Technol. Vol 32 279-288
6. Holmberg S, Enquist B and Thiderkvist P 2004 Evaluation of sheet metal formability by tensile tests J. Mater. Processing Technol. 145 72–83
7. Min J, Stoughton TB, Carsley JE and Lin J 2016 Compensation for process-dependent effects in the determination of localized necking limits Int. J. Mech. Sci. 117:115–34.
8. Ghosh A and Hecker S 1974 Stretching Limits in Sheet Metals: In-Plane Versus Out-Of-Plane Deformation Metallurgical Transactions A 6A 1665–69.
9. Sriram S, Huang G and Yan B 2009 Comparison of forming limit curves for advanced high strength steels using different technique SAE Int. J. of Mater. and Manufacturing 2 472–81.
10. Gutiérrez D, Lara A, Casellas D and Prado JM 2010 Effect of strain paths on formability evaluation of TRIP steels Adv. Mater. Res. 89–91, 214–9
11. Huang G and Sriram S 2014 Determination of Forming Limit and Fracture Limit Curves Using Digital Image Correlation SAE Int. J. of Mater. and Manufacturing 7, Issue 3, 574-82.
12. GDDRG 2012 Proposal for Revision of ISO 12004-2: 2008 (FLC determination in the laboratory) ISO TC164/SC2-Meeting Sao Paulo Brasil