

Comparison of Forming Limit Curves for Advanced High Strength Steels Using Different Techniques

S. Sriram, G. Huang and B. Yan

ArcelorMittal Global R&D, E. Chicago Center

J-L. Geoffroy

ArcelorMittal Global R&D, Maizières-lès-Metz

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ABSTRACT

Forming Limit Curves (FLCs) have been used in press shops for decades during die development and more recently as failure criteria when used in conjunction with FEA for part feasibility analysis. Around the world there are different techniques used to determine the FLC. The differences between the techniques lie in tooling, specimen geometry and in the method used to determine the critical strains. A comprehensive study on FLCs of selected AHSS was carried out at ArcelorMittal Global R&D, where the different commonly used techniques and a new technique employing Digital Image Correlation (DIC) were employed to determine the FLCs. This paper presents results of these comparisons.

INTRODUCTION

Forming Limit Curves (FLCs), which are combinations of critical major and minor principal strains have been in use since the pioneering works of Keeler [1], Goodwin [2], Hecker [3] and several other researchers. Traditionally, FLCs have been invaluable during die development, try-out, and troubleshooting failures caused by localized necking during stamping. Over the last decade, since the maturity of commercial Finite Element Analysis (FEA) in predicting strain states for automotive part geometries, FLCs have also been used

as failure criteria to evaluate forming feasibility during the early stages of product development.

Because of the tremendous importance of FLCs in the sheet metal forming community, there has been a considerable amount of research on FLCs of sheet metal involving many different aspects. In general, research and development efforts on FLCs can be divided into three main categories: (a) experimental determination (b) empirical predictions based on experimental data (d) theoretical calculations using principles of plasticity, instability theory, damage mechanics.

Experimental determination of FLCs consists of forming gridded samples till a failure point is reached. Different strain paths are generated by forming samples of multiple widths. While this is straightforward to understand conceptually, many differences exist in the details of experimental procedures which may potentially yield different results. Typically, in North America, Hecker's method [3] is used for generating the experimental FLC. This method is based on Nakazima's experimental technique of obtaining different strain paths [4]. FLC is determined by plotting a curve that demarcates between "safe" points and "necked" points in strain space. Of vital importance is the identification of a measured point as a necked point. This is most often determined by visual observation and touching the sample. Because of the subjective nature of the determination of necked points, a large number of

samples need to be formed and measured. It is not uncommon to have a large spread in the strain values for the necked points. The advantage with this method is that it is closest to the evaluation technique used in a press shop environment. However the disadvantage lies in the fact that many samples and measurements are necessary to generate good quality FLCs. In Europe, a new ISO standard [5] for experimental determination of FLCs is currently under development. According to the standard, the FLC could be determined either using the Nakazima tooling or the Marciniak double blank method [6]. Samples are formed till fracture, and the strain distribution is determined across the fracture line. Limit strains are determined using an interpolation approach. This method does not require as many samples as the North American approach, but because the determination of critical strains is based on curve fitting instead of physical measurement, questions have always been raised about the validity of the measured critical points. Recently there have been several attempts to determine the critical strains using speckle based techniques used in conjunction with image processing. Edwards and co-workers [7] used electronic speckle interferometry to determine the forming limits for uniaxial tension and plane strain geometries. Situ and co-workers [8] also used a speckle pattern to determine the FLC using an online measurement system whereby images of the deformed sample are taken and post-processed to determine critical strains. Most recently, strain measurement using Digital Image Correlation technique (DIC) has resulted in experimental FLCs being generated [9]. Digital image correlation has become a cutting-edge tool for measuring surface displacement and strain of materials under deformation [10, 11]. It is an effective non-contact technique that can provide the full-field strain distribution during the deformation process. The methodology of DIC is based on the assumption that the pattern feature of a certain area of surface (e.g. paint particles, grids) does not change before and after deformation, and the displacement and strain field can be determined by comparing pixel by pixel between the deformed and undeformed images of specimens. Because of the existence of different experimental methods for FLC determination, it is natural to enquire into the sensitivity of experimentally generated FLCs to the different techniques.

Prediction of FLCs has also used different approaches, ranging from empirically based to theoretical calculations relying on instability analysis, and more recently damage mechanics. The early pioneering works in this area were due to Swift [12] and Hill [13] where the concept of instability during plastic deformation was used to determine forming limits for diffuse and local necking respectively. To calculate local necking limits under biaxial stretching, the classical M-K [6] approach has most often been used. In this approach, a pre-existing

defect in the sheet is conceptualized as a groove in the sheet metal. Using the constraint caused by the groove, whereby the minor strain along the groove is zero, and force equilibrium equations, the limit strains can be calculated. It is worth noting that the calculations of the critical strains are significantly dependent on the size of the pre-existing defect, yield function and the hardening law used for determination of the stresses. The most commonly used prediction for the FLC is due to the work of Keeler and Brazier [14], and subsequent work done by Riffle [15], where a standard shape of the curve is used. The curve is adjusted based on the n -value and thickness of the material. In North America, the "standard" FLC is very widely used for die development, die buyoff activities and routine problem solving in the stamping plant. Raghavan and co-workers [16] also developed a predictive equation for the plane strain forming limit, FLC_0 as a function of the total elongation and thickness of the sheet metal. This predictive equation is not very widely used. Cayssials [17] developed a set of predictive equations for different strain paths using instability analysis, damage mechanics coupled with experimental observations. The FLC determined using this approach does not have a standard shape. The model, (henceforth referred to as ArcelorMittal Europe model) is a function of the strain rate sensitivity, uniform elongation, r -value and thickness. In subsequent work, a correlation between the ultimate tensile strength and strain rate sensitivity were established and the predictive FLC is now expressed as a function of uniform elongation, ultimate tensile strength, thickness and the normal anisotropy parameter, R . Validation of the ArcelorMittal Europe model was conducted for steel grades ranging in tensile strength from 260MPa to 1500 MPa and thickness upto 3mm with good results.

The goal of the current work was to compare the experimental and predictive FLCs of several lots of Advanced High Strength Steels. Testing was done according to the traditional North American (NA) and the ISO 12004-2 techniques and Digital Image Correlation. The experiments are also compared with the standard FLC used in North America and ArcelorMittal Europe model. Although the limitations of the basic FLC with respect to changing strain paths, bend severity, and sheared edges are recognized, these complications are not considered in this paper.

EXPERIMENTAL PROCEDURES

Table 1 shows the list of materials with typical mechanical properties used in this study. The mechanical properties were determined using the ASTM E-8/E 8M standard for tensile testing. In Table 1, CR stands for uncoated steel and GA stands for a galvanized coating. DP refers to the dual phase



microstructure and TRIP for transformation induced plasticity grade. TRIP steels have a small percentage of retained austenite in the microstructure that transforms to martensite upon deformation. The DP980SF steel grade has a higher YS/UTS ratio and has been developed specifically for stretch flanging applications.

Table 1: Steel grades and basic mechanical properties.

Grade	t (mm)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Test method
CR DP590	1.0	370	613	15.5	24.5	NA, ISO
	1.4	373	622	14.5	22.4	NA, ISO, DIC
CR DP780	1.2	519	851	10.4	15.8	NA, ISO, DIC
GA TRIP780	0.96	475	804	13.6	18.6	NA, ISO, DIC
CR DP980SF	1.6	871	1025	6.7	12.0	NA, DIC

Also listed in Table 1 are the test methods for determining the FLC. NA stands for traditional NA method, ISO stands for the newly developed ISO standard and DIC stands for Digital Image Correlation technique. A description of the different testing methodologies is described below:

TRADITIONAL NA TECHNIQUE

Using the traditional North American approach for FLC determination, samples were formed using a 101.6mm hemispherical punch. The sample size was 'w' X 177.8mm. Here, 'w' is variable and ranges from 25.4mm to 177.8mm. For sample widths less than 101.6mm, the samples were "waisted" (reduced section in the middle) to promote failure in the punch contact region. Samples were electrochemically gridded using a circular grid of diameter 2.54mm. The specimens were lubricated using Ferrocote® MAL HCL1 (prelube). For equi-biaxial stretching, a sheet of PTFE (Teflon) was also used in addition to the prelube. Initially samples are formed till a predefined load drop (typically 5%) is detected. At this point, the samples show very significant necking or fracture. After determining this failure height, testing is done by trial and error to form samples just below the failure height. Typically 8 to 10 samples per width are formed. The incipient neck is most often determined by touch. Once the circles exhibiting incipient necking were determined, strains were determined using an FMTI

camera system [18]. The experimental FLC was then drawn as a lower bound to the necked points. Figure 1 shows the formed specimens for determination of FLC using the traditional NA technique. The biggest drawback of this technique is that it takes a considerable amount of time to generate an experimental FLC. The FLC generated using this approach is also dependent on the skill and experience of the operator.



Figure 1: Samples formed using the traditional NA technique for determination of FLC
ISO 12004-2 TECHNIQUE

In this method, samples were formed using the Marciniak punch, which is a flat-topped punch with a circular recess. Carrier blanks with circular cut-outs were used during the forming process. This experimental feature enables determination of the FLCs while eliminating the effects of tool curvature and friction. Following standard practice in Europe, samples were electrochemically etched with a 2mm square grid. For determination of critical strains, the Bragard method [19] was used. Strain measurements were made along three lines of nine squares on each side of the crack. Measurements were made using the CAMSYS [20] image analysis system and dedicated software ASAME to determine the strain distributions along the three lines. For determination of critical strain values, the strain distribution was further analyzed to determine points inside the failed region. These points are then deleted from the strain distribution. An inverse parabola was fit through the remaining points of the strain distribution to determine the critical values of the major and minor principal strains. For further details, the reader is referred to the work by Bragard [19]. Figure 2 shows the test samples used for FLC determination using the ISO 12004-2 approach. This technique does not mandate the use of a Marciniak punch. For the purpose of this study, both Marciniak and Nakazima tooling were used in conjunction with the strain analysis system to isolate the effect of tool curvature and friction on the determined FLC.