

Determination of Forming Limit and Fracture Limit Curves Using Digital Image Correlation

Gang Huang and Sriram Sadagopan
ArcelorMittal USA

Hubert Schreier
Correlated Solutions Inc.

ABSTRACT

Forming limit curve (FLC) and fracture forming limit curve (FFLC) are valuable tools for failure prediction in forming simulation and die try-out in press shops. In this paper, methods are presented to determine FLC and FFLC for sheets of advanced high strength steels (AHSS) using digital image correlation (DIC). Dome tests were conducted on AHSS specimens using DIC system for strain measurement. For generating FLCs, two approaches are introduced to determine the onset of localized necking by analyzing the strain history at critical locations, one of which has been implemented into the commercial DIC software Vic-3D (Correlated Solution inc.). For determination of FFLC, a method for measuring fracture strains based on the strain path evolution is presented. The measured FLCs for several AHSS were compared to the FLCs using ISO 12004-2, and conventional North American experimental measurements and empirical equations. The results of comparison revealed that FLCs using DIC are in good correlation with other existing data, thus validating the presented methodologies.

CITATION: Huang, G., Sadagopan, S., and Schreier, H., "Determination of Forming Limit and Fracture Limit Curves Using Digital Image Correlation," *SAE Int. J. Mater. Manf.* 7(3):2014, doi:10.4271/2014-01-0982.

INTRODUCTION

Forming Limit Curve (FLC) is a map of principal strains that delineates safe region from failed region for sheet metals and is a very useful tool to determine formability limits in stampings. Since the FLC of steel is able to predict the necking during sheet forming process, it provides a failure criterion for Finite Element Analysis (FEA) to judge if the part is feasible with the specified grade in the part design.

Fracture forming limit curve describes the strain limit of material that can be formed without fracture. Although FLC is more often used for failure prediction in sheet forming process, FFLC with limit of fracture strains is also of important input when fracture prediction is required, such as in crash simulations.

Several deformation methods exist to acquire FLC, among which the most often used ones are Nakajima [1] and Marciniak tests [2]. The Nakajima test uses a spherical shaped dome, while Marciniak test uses a flat topped dome. For both testing methods, specimens with a series of widths are used to generate different strain paths. The conventional method of determining FLC is to measure the strains just before incipient necking by reading circle grids which were electrochemically etched on the surface of the sheet. In North America, Nakajima

test is normally used, and the experimental method to catch the incipient necking is by trial and error. A series of specimens are formed first to different heights with different necking conditions. Thus the test can be controlled such that it is terminated at the moment when localized necking is initiated. This process is done by visual observation or hand feel, thus the test is time consuming (almost one month per steel) and often carries large error. In Europe, conventionally a position dependent approach was used to determine incipient necking strains for sheet metals formed with Nakajima or Marciniak testing method, where limit strains from different strain paths were calculated by the extrapolation of strain distribution in the failure zone before or after fracture occurred [3]. This FLC determination approach evolved into ISO 12004-2 [4].

In the last several decades, Digital Image Correlation has been increasingly applied in mechanical characterization of sheet metal due to the fact that DIC as a non-destructive technique is able to provide measurement of full-field strain history in a fast and accurate fashion compared to most conventional strain measurement methods. The mechanism 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. Figure 1 shows the schematic of DIC mechanism. During DIC analysis, in the undeformed image a subset is first designated around the point where strain will be measured, then the point of interest on the deformed images is tracked by matching the subset between deformed images and reference image based on the assumption that the feature (e.g. gray scale) does not change after deformation of specimen. Once the point of interest is tracked, the displacement and thus the strain can be determined.

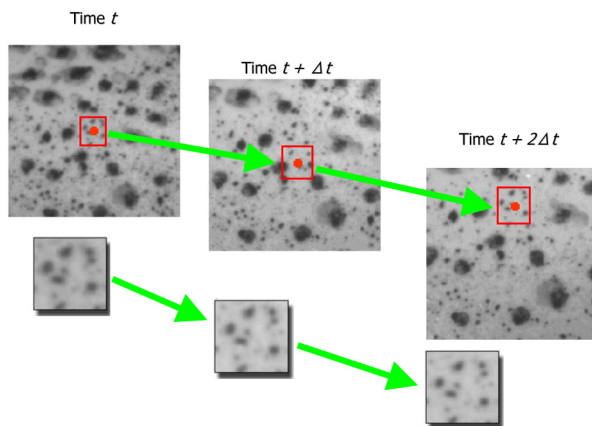


Figure 1. Schematic of tracking process in DIC analysis

With the high popularity of its application in deformation measurement, DIC has been recently also used in determination of FLC. There are two categories of incipient necking criteria to generate FLC. One is the position dependent approach, which is aligned with the ISO 12004-2 to determine the limit major/minor strains using an inverse parabola fitting of designated length along cross-section lines perpendicular to fracture line on both sides of necking zone [4]. The other category is of time-dependent approaches, which analyzed the evolution of strain(s) at critical location(s) from DIC to determine the moment of incipient necking. Huang et al. developed a criterion based on the peak of the second derivative of strain with respect to time for determination of the moment of incipient necking [5]. Volk proposed a method of strain rate frequency diagram from which the onset of necking is assumed at sudden increased number of measurement

points for higher strain rate inside the necking zone [6]. Feldman et al. presented a criterion for incipient necking based on the assumption that necking started when the rate of difference between maximum and average strains in the necking zone diverged from initial linearity [7].

The main advantage of the position dependent approach is that only a few images are needed to generate limit strain point at specific strain path. However, the limit strains are determined only by postulation using curve fitting without direct access to the real moment of incipient necking. For time-dependent approaches, the advantage over the time-dependent approach is that strains are temporally analyzed to detect the incipient necking moment; however, the varied methods depend heavily on the mathematical assumption and process to find the onset of necking.

It has been reported [7,8] that all the position-dependent and time-dependent approaches tend to generate FLCs close to those using the conventional method or ISO 12004-2 practiced in Europe. Prior to this paper, no approach was reported that can match the FLC data with North America (NA) experimental method or the Keeler -Brazier equation. To provide an accurate and efficient way to generate FLC data which match NA experimental method/K-B equation, an incipient necking criterion with mixed time and position dependent approach has been developed at ArcelorMittal Global R&D, and is presented in this paper.

The approaches presented in this paper for determination of FLC are based on strain measurement from DIC. Two criteria to determine incipient necking are presented, and the resulting FLCs of several materials are compared with conventional data. Meanwhile, a method to determine FFLC using DIC is also presented.

EXPERIMENTAL PROCEDURE

Materials

Seven materials were used in this study. Table 1 shows the list of materials with tensile properties. The properties were determined using the ASTM E-8 standard for tensile testing.

Table 1. Steel grades and tensile properties

Grade	t (mm)	Coating	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
DQSK CR	0.8	Uncoated	170	310	27	44
DP590 CR	1.4	Uncoated	373	622	14.5	22.4
TRIP590	1.54	GA	412	650	22.8	29
DP780 CR	1.2	Uncoated	519	851	10.4	15.8
TRIP780	0.96	GA	475	804	13.6	18.6
DP980SF	1.6	Uncoated	871	1025	6.7	12
M900	1.2	Uncoated	910	1003	2.5	5.4



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 microstructure. TRIP steels have a small percentage of retained austenite in the microstructure that transforms to martensite upon deformation. M900 is a fully martensitic material. The DP980SF steel grade has a higher YS/UTS ratio and has been developed specifically for stretch flanging applications.

Experiment

A dome tester with DIC system was used to form a dome shape ([Figure 2](#)). An MTS servo hydraulic testing system was employed to conduct LDH tests where Nakajima testing method was applied. The steel blanks were 177.8 mm long with the width varying from 25.4 to 177.8 mm to represent different strain paths. A hemispherical punch with diameter of 4 inches was used. Tests were performed on 3-5 blanks for each width of each steel grade. The blanks were prepared with spray paint speckles on the surface. During the forming process, two cameras oriented with a fixed angle were positioned above the forming equipment, as shown in [Figure 2](#). Images of the specimen and the speckle pattern were recorded simultaneously by the two cameras at speed of 15-20 frames/second during forming until fracture occurred. Then the dedicated DIC software, Vic 3D (from Correlated Solutions Inc.), was used to analyze the acquired images to calculate the major and minor strains of every point of the deformed specimens at each imaging moment.

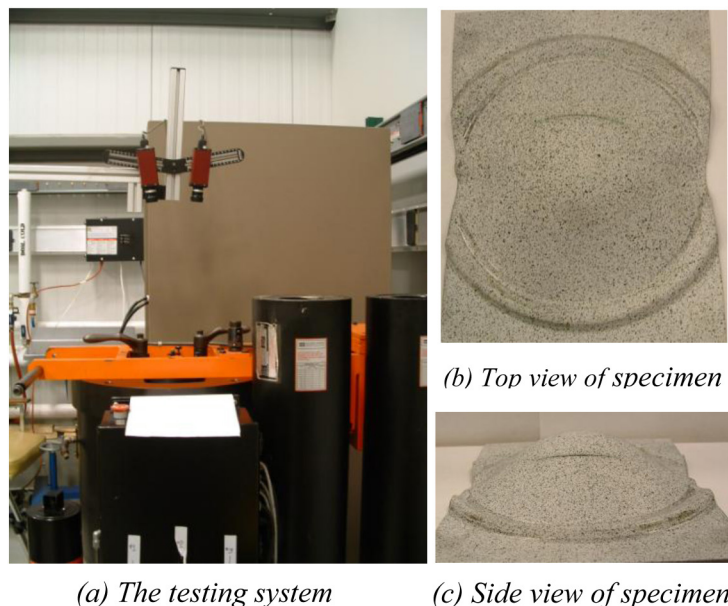


Figure 2. Setup of LDH test using DIC system and LDH specimen

For comparison, conventional measurements of FLC based on NA experimental method and ISO 12004-2 were also conducted. The experimental procedures of ISO 12004-2 are detailed in reference [4]. Using the NA experimental method, the samples (width of 25.4 to 177.8mm and length of 177.8mm) were first electrochemically gridded with circles of

diameter 2.54mm, as shown in [Figure 3](#). Then the samples were formed with trial and error to acquire the testing outcome with incipient necking based on finger touch. Thereafter, the samples with incipient necking were inspected with a camera system to measure the strains, and then FLC was drawn as lower bound to the necking points. The major drawback for this technique is that it needs considerable amount of time to generate one experimental FLC, and it is dependent on the skill and experience of the operator.



Figure 3. Samples formed using the traditional NA technique for determination of FLC

For determination of FFLC using DIC, the same experimental procedures for FLC were applied, where the samples with different widths were formed up to fracture, and pictures acquired by cameras were analyzed to determine the fracture strain for different strain paths.

INCIPIENT NECKING CRITERIA

Two incipient necking criteria have been developed to determine FLCs of AHSS at ArcelorMittal Global R&D-East Chicago. The first criterion was based on the time-dependent behavior of major strain history at the critical position where fracture occurred. The second criterion was based on the strain history relationship between the critical position (with ultimate fracture) and other position; therefore it is of a method of mixed time-dependence and position dependence.

Criterion 1

It is assumed that when the necking occurs inside the sheet metal through thickness direction, the major strain or minor strain is subject to some instant change caused by instability. This should be reflected by the change of strain or derivative of some order.

[Figure 4](#) shows an example dome sample after fracture and its contour of major strain distribution determined from DIC on the picture frame right before fracture. The position with maximum major strain on the contour was selected as the critical point where the necking and fracture occurred, as shown in [Figure 4](#).