Journal of Achievements in Materials and Manufacturing Engineering

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

# Difference between 2D and 3D capturing and influence of strain rate on FLC diagram of DC.01 steel

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Received 03.04.2014; published in revised form 01.07.2014

**ABSTRACT**

**Purpose:** The aim of this work is to develop a method for evaluating forming limit curves measured at high strain rates using drop tower while specimens are being captured by high-speed camera (2D).

**Design/methodology/approach:** This article describes the first step to establishing such method – verification of compatibility between 3D and 2D capturing by ARAMIS system.

**Findings:** Within this work, FLD recorded in 3D and 2D mode were determined. After correction of the angle α between projection onto the normal plane to direction of loading and tangent in the point where crack occurred, the obtained FLD diagram were almost identical.

**Research limitations/implications:** Optical methods, such as digital image correlation used by ARAMIS measuring system, offer very detailed information of material's surface at high resolution while significantly reducing the preparation and evaluation time for specimens testing.

**Originality/value:** The analysis of true plane major strains in the forming limit diagram (FLD) is still the most established method for failure detection of sheet metal forming processes in industrial praxis. With the prerequisite of linear strain paths it is very simple to predict the start of necking by using the FLD.

**Keywords:** Forming Limit Diagram; Optical measuring; ARAMIS; 2D vs. 3D

**Reference to this paper should be given in the following way:**

L. Potužník, P. Konopík, M. Rund, Difference between 2D and 3D capturing and influence of strain rate on FLC diagram of DC.01 steel, Journal of Achievements in Materials and Manufacturing Engineering 65/1 (2014) 32-37.

ANALYSIS AND MODELLING

## 1. Introduction

Forming Limit Curve (FLC) is an empirically derived curve showing the biaxial strain levels beyond which localized through-thickness thinning (necking) and subsequent failure occur during the forming of a metallic sheet [1]. The strains are given in terms of log major and minor strain measured after forming a series of test specimen blanks by using a grid pattern or optically.

The analysis of true plane major strains in the Forming Limit Diagram (FLD) is still the most established method for failure detection of sheet metal forming processes in industrial praxis. With the prerequisite of linear strain paths it is very simple to predict the start of necking by using the FLD [2]. The influence of strain rate on the FLD is a very interesting research topic, e.g. for automotive industry. The aim of this research is to describe the influence of strain rate of FLD up to dynamic loading of 20 m/s. Such speed is possible to reach using drop tower with high-speed camera but the record is possible only in 2D capturing. Therefore, the first step of this research work is to develop a method for FLD determination using 2D capturing.

## 2. Forming limit diagram measurement

Forming limit curves (FLC) of two sets of specimens manufactured from 1 mm thick DC.01 sheet were measured using ARAMIS measuring system (Fig. 1) [3]. Each set contained 18 specimens (3 specimens for six different geometries). The first set was measured using both cameras (3D) and the second using only one camera (2D).

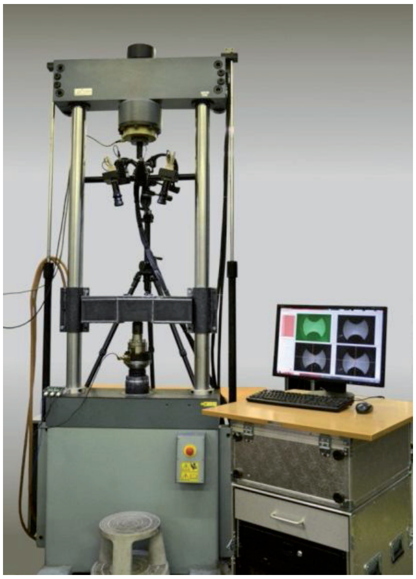

Fig. 1. Test setup

### 2.1. Forming limit diagram measured in 3D

3D capturing is a classic method for FLC measuring. The objective was to obtain reference FLD curve for DC.01, which could be later used to confirm accuracy of corrections made to data acquired by 2D capturing.

Prior the testing, stochastic pattern is applied on the surface of the specimen as can be seen in (Fig. 2).


Fig. 2. Specimen with applied pattern

All measurements were done in accordance with the standard ISO 12004-2:2008 [4] under the following conditions:

- recording speed of 10 frames per second,
- cupping speed: 1 mm/s,
- temperature: 23°C ± 5°C.

Multilayer lubrication system was used for reducing the friction. The test end was defined by a rapid decrease in load.

Under the load, the specimen is deformed and so is the applied pattern. ARAMIS system tracks the grey value patterns in images recorded during the test. Images are compared to each other to detect displacement of selected point. As single point is too difficult to find, an area of several points, in ARAMIS called facets, is tracked instead. Every facet has unique distribution of grey level (i.e. light and dark pixels of varied light intensity). Based on assumption that grey level of each facet does not change during the test, individual facet is located in reference image and all following images. From changed position of tracked facet displacements, strains and other quantities can be calculated. Example of specimen image with computed facets is in Figure 3.

For FLC computation only the last image before the crack initiation is used. Three intersection lines are created in the image. First line goes through the centre of oncoming crack, as perpendicular as possible to it. Further two sections are positioned on each side of the first one, symmetrically, at a 2 mm distance. Lines are as long as possible to cover full range of displayed strain, but not up to the edge of the specimen.

The goal is to get the values of $\varepsilon_1$- $\varepsilon_2$ pair, where $\varepsilon_1$ is major true strain and $\varepsilon_2$ is minor true strain. First "bell-shaped" curve is extracted. This curve represents values of major and minor strain in each point of intersection line (Fig. 4). Then the best fit curves – modified inverse parabolas f(x)=1/(ax2+bx+c) – are calculated. The blue and red cross-points in Figure 4 are the ones used for fit curves calculation. The intersection values of these curves with crack position are defined as the desired $\varepsilon_1$- $\varepsilon_2$ pair values, used for final FLC diagram. These values define the beginning of instable necking.

Complete forming limit diagram is shown in Figure 5. Values of $\varepsilon_1$- $\varepsilon_2$ pairs are represented by blue dots, the average for given geometry is shown as a red dot.

## 2.2. Forming limit diagram measured in 2D

The test setup and the first step of evaluation was the same as in previous case, except for this time only one camera was used for capturing. Obtained FLD, before using any kind of corrections is pictured in Figure 6.

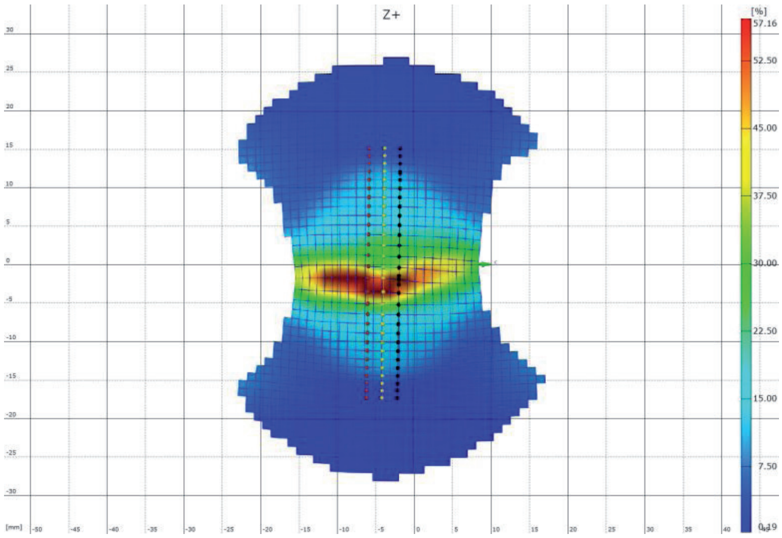


Fig. 3. Image from ARAMIS software with calculated facets

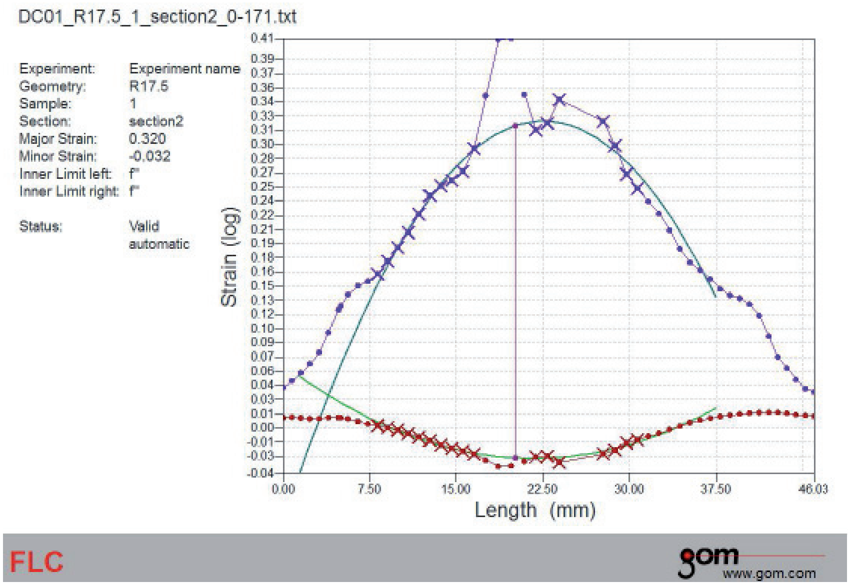


Fig. 4. Strain values through intersection line

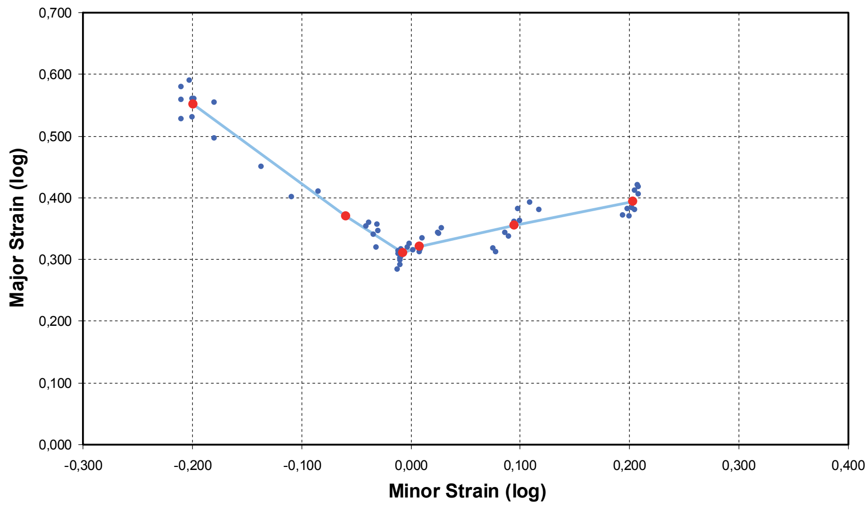


Fig. 5. Forming limit diagram of DC.01 captured in 3D

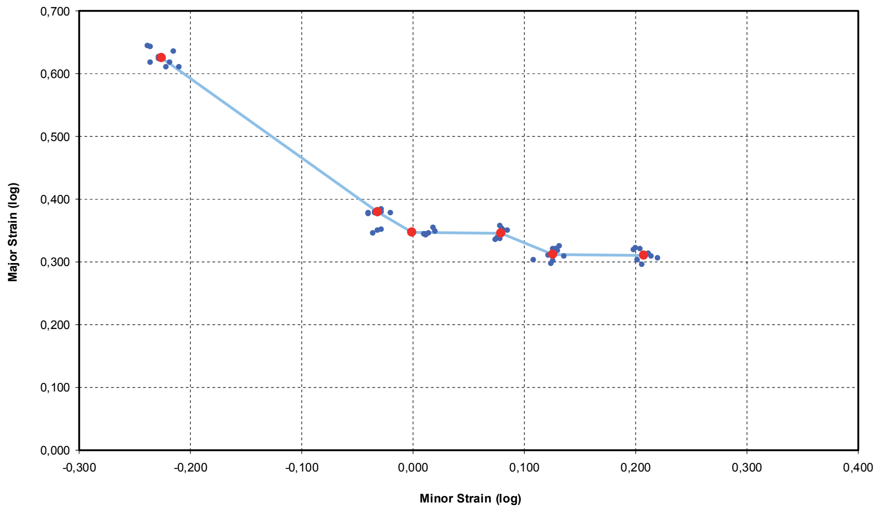


Fig. 6. Forming limit diagram of DC.01 captured in 2D before using corrections

As can be seen the part of the diagram where minor strain reaches positive values does not reflect real behaviour of the material. It is caused by inability of 2D measuring system to determine changes in distance between camera and specimen during cupping. The camera sees the specimen as flat plane and if the crack occurs somewhere on the side of hemisphere (Fig. 7), the evaluating software computes major strain values, which are lower than the actual. That was the case with the first three geometries.

Therefore correction of those values had to be made. The angle α between projection onto the normal plane to direction of loading (which is the length what the camera can see) and tangent in the point where crack occurred was determined. Based on this angle, the real major strain value was computed according to equation (1):

$$M = \frac{M_0}{\cos \alpha} \quad (1)$$

where $M_0$ is major strain value computed by ARAMIS, and α is aforementioned angle. After applying those corrected values to diagram above, the final FLD was obtained (Fig. 8).

When comparing this diagram to the one captured in 3D we are getting promising results (Fig. 9).

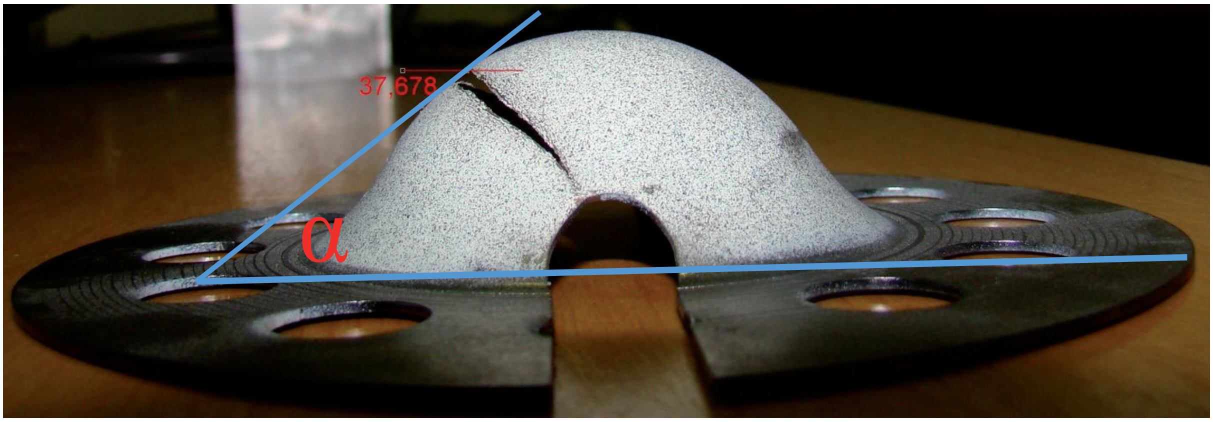


Fig. 7. Example of specimen with crack on the side

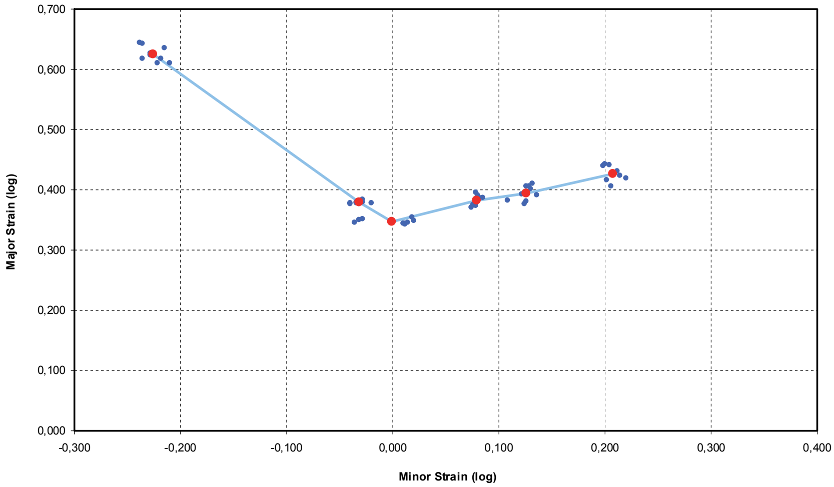


Fig. 8. Forming limit diagram of DC.01 captured in 2D after using corrections

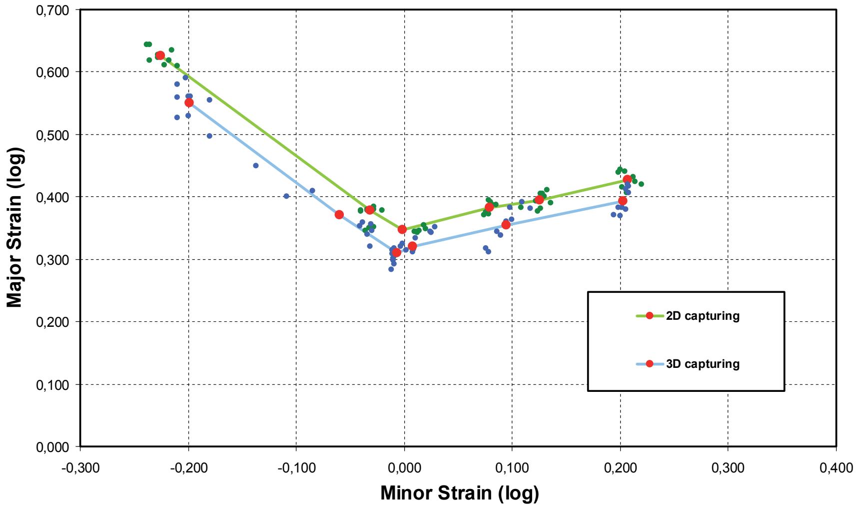


Fig. 9. Comparison between both ways of capturing

## 3. Conclusions

Within this work, FLD recorded in 3D and 2D mode were determined. After correction of the angle α between projection onto the normal plane to direction of loading and tangent in the point where crack occurred, the obtained FLD diagram were almost identical. The future goal is to measure another two sets of specimens, one using high-speed camera for capturing and test conditions specified by ISO 12004-2:2008 and the other also with high-speed camera, but now with specimens tested on drop tower at high strain rates. Procedure for correcting measured values, so they correspond to 3D results, will be determined.

## Acknowledgements

This work was done within the work on project ED3.1.00/14.0309 – Development of pre-seed activities in COMTES FHT.

## Literature

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