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Published in:
11th International Congress and Exhibition on Experimental and Applied Mechanics 2008

Published: 01/01/2008

Document Version
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:
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• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

Citation for published version (APA): 
In-Plane Biaxial Loading of Sheet Metal until Fracture

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ABSTRACT

The last decades have seen a tremendous effort to analyze and understand the strain path dependency of sheet metals until fracture for incorporation in advanced forming simulations. Compared to Nakazima tests, which are traditionally used for experimental verification of these simulations, in-plane biaxial loading (IPBL) has the advantage of well-known boundary conditions, full control of the followed strain path, and possibility for online microscopic inspection. The use of IPBL setups, however, is limited by the geometry of the cruciform specimens which are reported to fail away from the central region when tested until fracture. This work solves this issue by addressing the cruciform shape. Elasto-plastic FE simulations demonstrated that a significant thickness reduction in the cruciform center is necessary to reach fracture in the biaxial strain path. Specimens of this geometry are produced using electro-discharge machining (EDM) and extensive characterization using scanning electron microscopy revealed no significant microstructure distortion during the EDM process. A biaxial testing apparatus for IPBL until fracture was developed and digital image correlation was applied for local strain determination. The obtained local strains revealed good correlation with the simulations.

1. INTRODUCTION

There is an ever-lasting effort in the automotive industry to improve the predictive capabilities of forming simulations, in order to minimize the production costs of car components. This effort requires improvements to the currently used continuum models, especially after the reports on unpredicted damage-driven failures of the new advanced high strength steels (TRIP and dual-phase) [1]. In the biaxial strain path, for example, it is observed for these metals that the experimentally obtained fracture limit curve approaches (and in some cases intersects) the forming limit curve [2]. This type of damage-influenced fracture sensitivity is not captured in the currently used models. Furthermore, it has long been known that the formability limits of sheet metals are heavily dependent on the exact strain path that they follow [3], as shown in figure 1. Complex forming paths are frequently used in the industry to improve the formability of the sheets (e.g. from line I to line II in figure 1). However, most forming simulations used in the industry are not equipped with suitable tools to accurately predict the strain path dependency of the sheet to be formed.

Improving the predictive capabilities of these models require a better understanding the mechanical behavior of such metals, linking it to the underlying microstructural events. Of special importance is the connection between strain path (especially biaxial strain path) and microstructure (e.g. damage) evolution. Consecutively, techniques such as the out-of-plane bulge and punch tests and in-plane cruciform tests are commonly used in the industry to investigate these effects. However, both bulge tests and punch tests have significant limitations. For the punch test there are always bending and friction effects, which makes it a challenge to accurately predict the exact stresses and strains involved in the deformation process. For the bulge test there is no friction effect, bending however is still to be taken into account together. In addition, high pressures are needed if sheet metals are to be tested to fracture, which prevents miniaturization and severely complicate to the use of sensitive online microscopic diagnostics. It is also noted that in general out-of-plane deformation tests are more complicated to
monitor with online full field measurements (e.g. digital image correlation) than in-plane tests. But most importantly, both punch and bulge test cannot be used to investigate complex strain paths.

![Forming Limit Diagram](image)

*Figure 1. Strain path dependency is shown on a forming limit diagram, as observed in many sheet metals. In a linear (i.e. one step) path the safe forming limits are designated with curve I. Initial stretching decreases the total formability (curve III), whereas initial drawing increases formability (curve II)*

Cruciform geometry, on the other hand, has the advantage that the region of interest is away from the boundary conditions, i.e. there are no complications due to contact or friction problems. Virtually any strain path can be applied to the specimen with much lower forces than for similar out-of-plane tests. Due to these reasons extensive amount of work has been carried out by many researchers on biaxial testing using cruciform geometries [e.g. 5-12]. However, in many of these studies the main goal is the determination of the yield surface for the tested material, therefore, these cruciform geometries will not localize in the center (figure 2). In fact, the cruciform has an intrinsic disadvantage that it is extremely difficult to deform the biaxially stretched region to the point of fracture. For this, the centre region of the cruciform shape needs to be weaker then the four arms to prevent failure in the arms instead of the centre. It is not possible to achieve this by only adjusting the in-plane geometry of the cruciform, as the width of the arms can not be larger then the diagonal width in the centre of the cruciform, as is graphically shown in figure 3.

![Cruciform Geometries](image)

*Figure 2. Different cruciform geometries as reported in the literature [13].*

![Cruciform Center](image)

*Figure 3. Center can never be weaker than the arms in a 'flat' cruciform specimen.*
Thus, to find an optimized specimen in which the yielding, localization and fracture occur in the center (where there is a biaxial stress state), either the center has to be weakened or the arms have to be strengthened. The goal of this present work is to investigate the possible use of a thickness-reduced cruciform geometry for multi-axial testing of sheet metal to the point of fracture. To achieve this, finite element simulations are carried out to obtain an idealized cruciform geometry. Different manufacturing methods are used for the production of the final geometry, which is then characterized via scanning electron microscopy to reveal any possible alterations to the as-received microstructure. Finally, biaxial tension tests are carried out together with local strain measurements to compare the strain localization in simulations and experiments.

2. EXPERIMENTAL & NUMERICAL METHODOLOGY

The material used in this work is a non-commercial interstitial free (IF) steel grade. It is a very formable steel which is often used in the automotive industry, and has a ferritic microstructure with equiaxed grains and a very low amount of inclusions, leading to an isotropic material behavior (figure 4).

![Figure 4. As-received microstructure of the non-commercial IF steel](image)

For the present purpose, elasto-plastic finite elements method (FEM-) simulations have been performed in MSC. Marc®. Plasticity is modeled with the piecewise linear method, using a table of equivalent plastic strain versus stress, as determined from uniaxial tensile tests. Using the FEM model several different in-plane geometries are modeled to investigate and compare the stress localization behavior.

![Figure 5. Link-mechanism designed to do the biaxial deformation of the produced samples. Inset picture shows the clamped specimen.](image)
To carry out the biaxial tension experiments, a link-mechanism is designed that can translate the vertical forces of a universal tension/compression test machine to four lateral axis, allowing the biaxial deformation of the cruciform specimen in the horizontal plane (figure 5). Note that all the joints only transfer the force in the vertical and radial direction, while the joints can move freely in the azimuthal direction, thereby preventing shear or rotational forces to be transferred to the specimen arms. This setup is placed within a compression machine and the specimen is clamped in the four central arms, as shown in the inset of figure 5. A random back-and-white micro-pattern is applied on the specimen for online local strain measurement by means of digital image correlation.

3. RESULTS AND DISCUSSION

Let us start with the results of finite element analysis of the unmodified cruciform geometry, shown in figure 6(a), where the von Mises stress distribution is given for the situation that the maximum level of stress is equal to the maximum stress reached in the tensile tests for IF steel. As seen here, the maximum stress is reached in the middle of the arms. In the attached graph (figure 6(b)), the competition between the three ‘candidate’ localization zones, the center, the corner and the arms of the cruciform is shown. Clearly the center endures the lowest stresses among these three.

Figure 6.   (a) Von Mises stress distribution on the unmodified cruciform specimen. (b) Stress built up in three different locations in the specimen, shown by the little black circles is Fig. 6(a), as a function of arm displacement. (c) Scale bar showing the von Mises stress level.

A first approach to make the center ‘weaker’ is to modify the corner geometry of the cruciform shape, following examples from the literature shown in Fig. 2. Figure 7 shows our best attempt to increase the stress level in the center relative to the arm and the corner, and indeed this ratio is much increase considerably compared to the situation of figure 6. However, as already explained above, such a strategy can never render the center to be weaker than the arms but only cause the localization to occur between the two corners, see figure 7(b).

Figure 7.   (a) Von Mises stress distribution of the cruciform specimen with a reduced arms width. (b) Stress built up in three different locations in the specimen as a function of arm displacement (c) Scale bar showing the levels of von Mises stresses
A second approach to carry the maximum stresses to the center of the specimen is to decrease the thickness of the center region. This can be done in three possible geometries, as shown in figure 8.

![Figure 8. Three possible thickness reduced cruciform geometries](image)

It is observed through finite element simulations that there are three important factors determining whether thickness reduction is successful in bringing localization to the center of the cruciform specimen. First, an optimum value for the radius of the region has to be determined. When the region is too large, stress localization may start between the corner of the thickness reduced area and the corner of the cruciform. When it is too small, the localization tend to occur in the arms, see figure 9. Second, the final thickness of the thickness reduced area is important. If the thickness reduction is not enough, than localization still occurs in the arms, see figure 10. On the other hand, making the thickness reduction too severe (such that a very thin section is left to be deformed) may introduce size effects to the observed material behavior. Third, the thickness reduction has to be carried out in such a way that the exact in-plane center of the specimen has the smallest thickness (as shown in figure 8 (b)), to obtain localization in the center point (figure 11(b)). When the whole thickness-reduced area has the same reduced thickness (as in figure 8 (a)), the localization initiates at the corner of the thickness reduced area (figure 11 (a)).

![Figure 9. Cruciform geometries with different thickness reduced area radius. The color scale bar is taken equal to the one shown in Fig. 6(c).](image)

![Figure 10. Cruciform geometries with a thickness reduction profile similar to figure 8(a) and with different levels of final thicknesses. The color scale bar is taken equal to the one shown in Fig. 6(c).](image)
Figure 11. Cruciform geometries with different thickness profiles, (a) as in figure 8(a); (b) as in figure 8(b). The color scale bar is taken equal to the one shown in Fig. 6(c).

As a result of these observations, the final optimized geometry is shown below in Figure 12(a). This geometry is manufactured using two methods using electro-discharge machining (EDM), see figure 12(b)). To analyze if EDM has a pronounced effect in the microstructure, the cross sections of the electro-discharge machined specimens are metalographically prepared for examination by scanning electron microscopy. This analysis revealed the existence of a non-continuous thin layer, a so-called ‘white layer’, reaching local maximum thicknesses of around 5 micron (figure 12(c)). Comparison of the average size of the grains in the machined center part with grains away from the machined part revealed a slight increase in the size of the grains (~10%) which are close to the material removed surfaces.

Figure 12. (a) The dimensions of the ‘ideal’ cruciform geometry, (b) a picture of a manufactured thickness reduced cruciform specimen, and (c) the EDM-influenced thin layer in the material removed surface.

The produced specimens are then tested in the biaxial testing setup, and the local strains are captured by the use of a digital image correlation software. The load-displacement curve of one of the biaxial tests are given in figure 12. As expected from the FEM simulations, all of the tested specimens failed in the center (figure 13(b)), with identical strain distributions and thus showing good reproducibility (figure 14). The crack is initiated in the center point of the cruciform and then followed its path towards the corners of the center section.

Figure 12. Load-displacement curve obtained from a biaxial test. Here, the displacement is the vertical displacement of the clamps to which the biaxial testing setup is fixed.
Further work involves the full characterization and testing of the cruciform specimen prepared with EDM. These results will be compared with results from specimens manufactured with another technique, i.e. electro-chemical machining. Finally, when the complete methodology is operational, thickness reduced cruciforms of various sheet metals will be measured to obtain its complex strain path dependence.

4. CONCLUSIONS

In this work one of the ‘holy grails’ of sheet metal testing, biaxial tension until fracture, is studied. Due to many advantages mentioned in the Introduction, the thickness reduced cruciform geometry is taken as the specimen geometry. An idealized specimen geometry is determined using finite element simulations. The most important finding here is that the cruciform specimen needs to have the smallest thickness at the center of the cruciform. In other cases (even when there is a thickness reduced area of constant thickness), it is not possible to achieve localization in the center of the biaxially deformed region. Specimens were prepare using electron discharge machining, which is observed to have a slight effect in the microstructure of the tested sheet. Biaxial tension experiments in the specially-designed setup revealed that failure is obtained as predicted in the FEM simulations.

ACKNOWLEDGMENTS

This work is funded by Materials Innovation Institute (M2i) project 2.05205, which is gratefully acknowledged. The authors would also like to thank Roel Vos and Ron Peerlings for their contributions to the results.
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