Investigation of non-proportional load paths by using a cruciform specimen in a conventional Nakajima test

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Abstract. The prediction of necking in sheet-metal forming is one of the most important tasks in the simulation of forming processes. The most common way to predict the necking for linear load paths is the Forming Limit Diagram (FLD) according to ISO 12004-2. This criterion is valid only for linear load paths. For non-proportional loading paths, Volk introduced a Generalized Forming Limit Concept (GFLC). This model enables the prediction of the formability for any non-proportional loading paths. The experimental investigation of those loading paths is still very challenging and complex. It involves a wide range of testing equipment for the pre- and post-strain of specimens. Jocham introduced a new method that allows the investigation of various non-proportional loading paths by using a cruciform specimen and a draw bead tool in a conventional Nakajima test setup. The height of the draw beads can be varied to create different load paths in the specimen centre. Nevertheless it is necessary for the thinnest part of the specimen to be in the middle of the specimen. This is achieved by milling an indentation into the centre. This mechanical procedure affects the formability of the material. In this paper, the cruciform specimens are laser weld from three single metal sheets in order to minimize the influence of the manufacturing process on the specimen. With this procedure, it is possible to test unmanufactured sheets. However, the crack still occurs in the centre of the specimen. With the new cruciform specimen, we are able to create arbitrary non-proportional strain paths.

1. Introduction

Most sheet-metal parts produced in press shops are produced using several forming steps. These forming steps lead to non-proportional load paths of the sheet metal. To guarantee high efficiency and quality, most parts are developed using Finite Element Analysis programs. The calculated true strains are compared to the linear Forming Limit Curves (FLCs). A linear FLC is only applicable if proportional loading occurs during the forming processes. Non-proportional load paths have a great impact on the formability of the sheet metal according to experimental studies of Bergström and Ölund [1] and Graf and Hosford [2]. To resolve this problem, a phenomenological approach was introduced by Volk [3]. This approach can predict the localized necking and the remaining formability for arbitrary non-proportional load paths. The database used for the GFLC requires several non–proportional experiments. Those experiments are very complex and need different specimen geometries, tools and machines. As there is no standard for the testing of non-proportional stretching, many different approaches have been deployed. Jocham et al. [4] used 3D-laser cutting of preformed Nakajima specimens to create non-proportional load paths. Due to the fact that the specimens gets reduced in size with every cutting, only some strain paths can be covered. This problem can be solved by using a modified Marciniak tool for
the pre-straining of specimens, see [5]. The area with a homogeneous strain distribution is large enough for all widths of Nakajima specimen. This approach nonetheless requires multiple tools. In recent years, many authors have investigated cruciform specimens to evaluate yield loci. There are many different cruciform geometries for yield-loci determination [6-8]. Those specimens are optimised with regard to a homogenous strain distribution of a large area. At higher strains, those specimens rupture outside the evaluation area.

For the creation of non-proportional load paths, different cruciform specimens must be used. Leotoing et al. [9] used an in-plane biaxial-tension test to determine localised necking. Their cruciform specimen has three different thickness areas produced by milling. Güler and Efe [10] also used a biaxial testing apparatus. Their CNC-milled specimen has an evaluation area of 2 mm in diameter and a thickness of 0.5 mm, with a roughness of Ra ~ 2 µm.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Different cruciform specimens, (a.) Leotoing et al. [9], (b.) Güler and Efe [10], (c.) Pascoe et al [6], (d.) Song et al. [11]

Yong et al. [12] used laser deposition to strengthen the arms of their cruciform specimen to achieve higher strains. The laser deposition led to an increase in equivalent plastic strain from ~0.03 to ~0.11. Jocham et al. [4, 14] used a blank holder with adjustable draw beads to create non-proportional load paths. This test setup allows all tests to be performed on one standard Nakajima testing machine. The height of the draw beads can be adjusted between 0 and 7 mm. Those draw beads were used to define different load cases. We used 2 mm-thick AW-5754 with an indentation in the specimen centre. The reduced thickness of 0.7 mm in the centre ensured that the crack occurs in the evaluation area.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Draw bead tool used by Jocham et al. [3]

The tool of Jocham et al. [14] is used in this paper to test optimised laser-welded cruciform specimens. The results of the cruciform specimens are compared to a linear FLC obtained from a standard Nakajima test. Further non-proportional load paths are determined and evaluated by the Generalized Forming Limit Concept (GFLC) by Volk [3], to prove the validity of the criterion for complex load paths.

2. **Experimental setup**

A ZwickRoell BUP1000 is used for the experimental results. A maximum punch speed of 3000 mm/min and a clamping and punch force of maximum 1000 kN can be provided by this sheet-metal testing machine. Measurement of strain is achieved by the optical measurement system GOM ARAMIS™ 4M. The measurement frequency is 10 Hz, according to ISO 12004-2 [1]. To suppress friction between the punch and the specimen, a PVC disc and grease are used. The evaluation of forming limits is performed using the Time Dependent Evaluation Method (TDEM) proposed by Volk [15]. The draw bead tool can be used in combination with a standard Nakajima punch. By using this tool, only one specimen geometry is needed to evaluate the complete linear forming limit curve. In order to achieve high strains and to
minimise the influence of the manufacturing process by milling, the cruciform specimens used are laser-weld. Three single HC340LA sheets with an initial thickness of 1 mm are welded together, see Fig. 3.

Figure 3. Laser-welded cruciform specimen

The three single sheets were manufactured by laser cutting. It was possible to generate high strains in the centre of the cruciform specimens through the slits in the arms of the specimens and the thickness ratio between the arms and the specimen centre, which is 3:1. Simulations have shown that the radius between the arms of the specimen is a crucial parameter in the uniaxial load case. The chosen radius of 2 mm is a good compromise between a good formability and a functioning specimen.

Table 1. Mechanical properties of the micro alloyed HC340LA steel

| Material | Thickness [mm] | Rp0.2% [MPa] | Rm [MPa] | Ag [%] | A80 [%] |
|----------|----------------|--------------|----------|--------|---------|
| HC340LA  | 1              | 333          | 419      | 19.45  | 32.63   |

To verify the concept, a forming limit curve consisting of four different strain ratios was determined. The results were compared to a standard forming limit curve obtained by conventional Nakajima test. To investigate the influence of the welding process, micro-hardness measurements and optical microscopic observations at the specimen centre were performed.

3. Results and discussion

3.1. Influence of the welding process on the material parameters

The welding process and the heat introduced into the material affect the microstructure. In order to quantify that influence, the centre of the specimen was investigated in the form of hardness measurements. Due to the fast welding process, the amount of introduced heat is relatively small. Nevertheless, the welding process leads to an increase in hardness in the weld seam – from an average Vickers hardness of 170 HV0.5 to one of 240 HV0.5.

Figure 4. Influence of the welding process on the micro hardness
The heat-affected zone (HAZ) and the weld seam are approximately 1 mm wide. In the evaluation zone of the specimen, no effect on the micro-hardness could be quantified. Quantitative microstructural analysis shows that the ferritic base material is transformed into a martensitic and bainitic microstructure, which leads to an increase in micro hardness.

3.2. Verification of the laser-welded cruciform specimen
To verify the new cruciform specimen, the results obtained from the linear Nakajima test were compared to the results performed on the draw bead tool. For both forming limit curves, the orientation of the specimens was 90° to the rolling direction.

![Figure 5](image)

**Figure 5.** (a) Comparison of the forming limit curves obtained by standard Nakajima and cruciform specimen, (b) Fracture location in the evaluation area of the specimen

The two forming limit curves show almost no difference in strain level. Only the uniaxial and biaxial strain paths differ. The material flow in the uniaxial experiments is limited by the arms of the specimen and the biaxial pre-forming, due to the hemispherical punch curvature. Nevertheless it can be concluded that the laser-welded cruciform specimen is a reliable method for determining linear forming limit curves. As seen in Fig. 4 the crack occurs in the centre of the specimen and spreads to the weld seam around the centre. The draw bead heights used for the experiments are listed in Table 2.

### Table 2. Experimental setup for linear load paths

|            | uniaxial | plane strain 1 | plane strain 2 | biaxial |
|------------|----------|----------------|----------------|---------|
| **Draw bead height** | D1 = D3 = 7 mm | D1 = D3 = 7 mm | D1 = D3 = 7 mm | D1 = D3 = 0 mm |
| **Clamping force** | 400 kN | 400 kN | 400 kN | 400 kN |
| **Spacer** | 3.5 mm | 3.5 mm | 3.5 mm | - |

The draw beads of the two opposite draw beads are always at the same height. The spacer is used to create a clearance between the arms and the tool. Otherwise the complete cruciform specimen would be in contact with the tool and the material flow would be limited due to friction. The biaxial load path is achieved only by clamping: no draw bead is formed into the arms of the specimen. This enables a better material flow in the following forming steps.

3.3. Non-proportional load paths
The presented experimental setup can also be used to create non-proportional load paths. This requires an adjustment of the draw beads after a certain punch height is reached, shown in Table 3 for a bi-linear experiment, by way of example. The resulting strains from the forming steps are optically measured and the evaluation of initial instability performed using the Time Dependent Evaluation Method [15]. To prove the possibility of creating multi-linear load paths with the presented experimental setup, three experiments with different strain paths were conducted.
The chosen draw bead heights lead to a non-proportional load path. The resulting necking point was predicted by the Generalized Forming Limit Concept, see [2]. The database for the GFLC-model was created using a pre-formed and standard Nakajima specimen, and is based on bi-linear load paths [16].

**Table 4. Comparison of the predicted strain path lengths**

| Load path   | Uniaxial – plane strain – biaxial   | Accuracy linear FLC | Accuracy GFLC |
|-------------|-------------------------------------|--------------------|---------------|
| Load path 1 | 89.03 %                             | 99.61 %            |
| Load path 2 | 86.19 %                             | 104.47 %           |
| Load path 3 | 98.14 %                             | 103.00 %           |

The linear FLC underestimates the formability of the material following a non-proportional load history; in comparison the GFLC shows good accuracy independent of the forming history of the material. Experiments with adhesive-bonded specimens were also conducted. Due to the high forces, the layers became delaminated. This led to an early failure of the specimen.

4. Conclusions

Using the presented laser-welded cruciform specimen, linear and non-proportional load-path experiments can be conducted. Even though the welding process leads to a heat-affected zone around the evaluation area of the specimen, this zone is approximately 1 mm wide, meaning that the effect on the mechanical properties can be ignored. The accuracy and feasibility of the proposed laser-welded cruciform specimen design has been validated by standard Nakajima experiments. For all experiments, the micro-alloyed steel HC340LA was used. The results correspond well to each other. A significant benefit of the draw bead tool in combination with the cruciform specimen is the possibility of creating non-proportional load paths with only one specimen geometry. Several non-proportional load-path experiments were conducted and the necking points compared to the predicted necking points using the Generalized Forming Limit Concept, which is based on bi-linear experiments. The predicted necking points, even for non-proportional load paths with more than two forming steps, are in very good agreement with the experimental results. As a next step the presented approach will be applied to
different materials and material classes like aluminium, high-strength steels and coated steels. The welding process for those materials has to be adjusted in order to minimize the influence of the welding process.

Acknowledgments
The authors would like to thank the financial support for this research provided by the German Research Foundation (DFG) with project numbers VO1487/15-1 and VO1487/34-1.

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