Semi–automatic approach for the creation of non-proportional load paths

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Abstract. Many industrial sheet metal parts experience a non–proportional loading history. The determination of such non–proportional loading paths on a laboratory scale is still very challenging and time-consuming. Most tests require different machines, tools and measurement techniques. Norz and Volk [1] have presented a new approach to create arbitrary non–proportional loading paths by using a cruciform specimen in combination with a draw bead tool. This simple experimental setup lead to a significant reduction in the experimental effort. It allows the generation of arbitrary loading paths by using only one machine, one tool and one specimen geometry without any further processing of the specimen between the forming steps. Nevertheless, the strain path could only be controlled manually after a certain forming step. In this paper, an in-line strain measurement was used to observe the real–time strain path during the experiment. This information was used to create a semi-automatic approach in which the draw bead height is adapted in order to create a prescribed strain path.

1. Introduction
The development of sheet-metal parts is often done by Finite element analysis (FEA) to reduce the try-out procedures. The accuracy of those FEA is dependent on reliable material parameters including the strength, anisotropy and formability. Following this, the characterization of the formability is done by Nakajima- or Marciniak tests according to ISO12004-2 [2]. These determined Forming Limit Curves (FLC) are only valid for proportional strain paths. Experimental studies of Bergström and Ölund [3] and Graf and Hoshford [4] have shown that the strain path history has a great influence on the formability of different materials. Therefore, different models have been introduced to predict this behaviour, for example the enhanced modified maximum force criterion (eMMFC) by Hora et al. [5], the polar effective plastic strain (PEPS) by Stoughton and Yoon [6] or the Generalized Forming Limit Concept (GFLC) by Volk and Suh [7]. The GFLC-model, as a purely phenomenological approach, needs a solid database consisting of different non-proportional experiments. Those experiments are often complex and time-consuming and not yet standardized. Hence, many different experimental approaches have been published. Jocham et al. [8] used laser cutted pre-formed Nakajima specimens to create non-proportional load paths. With this proposed method it is not possible to create arbitrary strain paths as the specimen width can only be reduced. To solve this problem, a modified Marciniak tool for the pre-straining of specimens can be used, see [9]. An area with a homogenous pre-forming allows the extraction of all widths of Nakajima specimen. Nevertheless, this approach needs several tools and optical strain measurement systems. Due to this, cruciform specimen were developed. One approach is the use of in-plane biaxial tension machines to determine the formability, see Leoting et al. [10]. Jocham
et al. [11] used a draw bead tool consisting of four independent draw beads on a conventional Nakajima testing machine in combination with a cruciform specimen. The height of the draw beads influences the retention forces and hence the strain path. A reduction of thickness in the centre of the specimen is needed in all presented approaches to ensure a crack occurrence in the evaluation area. Norz and Volk [1] have used a laser-welded cruciform specimen out of three single sheets in combination with the draw bead tool published by Jocham et al. [11]. This specimen, shown in Figure 1, was validated by conventional Nakajima tests and is capable to create non-proportional load paths.

![Figure 1. Laser-welded cruciform specimen according to Norz and Volk [1].](image)

The strains of the pre-formed specimens in the Marciniak tool or the draw bead tool can only be determined after the forming process. To create certain given strains specimens have to be formed and evaluated. It is necessary to know which draw depth leads to which strain. To overcome this problem, in-line measurement of the strains is necessary. In the recent years the real-time digital image correlation (DIC) has been further developed. Tian et al. [12] have improved a video extensometer to measure the strains in real-time for small strains. Wang et al. [13] and Huang et al. [14] have shown, that the real-time strain measurement requires high-performance computers in order to obtain a satisfying frame rate and a sufficient size of the evaluation area. The bigger the evaluation area, the lower the possible frame rate is. Blug et al. [15] have used the real-time strain measurement for controlling low cycle fatigue tests. A frame rate of 3 Hz was reached. This frame rate and the low latency of only 2 milliseconds allowed the replacement of the mechanical extensometer. The information obtained by the DIC-system can also be used for closed loop control. Fischer et al. [16] used a closed loop control in the production of sinks. They used information about the draw-in of the material to adjust the blank holder force. This approach lead to a stable production process. By using 3D-image correlation in combination with a closed control loop, Hao and Duncan [17] reduced the geometrical error in incremental sheet forming.

1.2 Experimental approach
The creation of non-proportional loading paths is a challenging task as described before. In this paper the real-time strain measurement is used to semi-automatically create arbitrary non-proportional load paths. Therefore, the draw bead tool of Jocham et al. [11] is used in combination with a control loop. The control loop compares a given strain increment to the measured strains in real-time. The flow chart of the control loop is shown in Figure 2.

![Figure 2. Flow chart of the LabView tool.](image)

The controlling of the draw bead tool is done by the software LabView™. Measured real-time strains from ARAMIS™ are transferred to a LabView™ tool. These strains are compared to a given strain increment. If there are deviations to the target strain increment or the target strain has been reached, the experiment is stopped and the draw bead height is adjusted. This adjustment is done by the testXpert™
software. The testXpert software to control the machine is also connected to a LabView™ tool which controls the draw bead heights. Nevertheless, the clamping of the specimens as well as the start of the experiment have to be done manually due to safety reasons. The initial draw bead height is set according to the first forming step. This approach reduces the experimental effort and allows an accurate creation of non-proportional load paths with defined strain increments.

2. Experimental setup
The draw bead tool is used in combination with a Zwick Roell™ BUP1000. This sheet metal resting machine allows punch speeds from 0.02 – 50 mm/s and has a clamping and punch force of up to 1000 kN. For the strain measurement the optical measurement system GOM ARAMIS™ 4M is used. The measurement frequency is 10 Hz according to ISO 12004-2. The onset of necking is determined by the Time Dependent Evaluation Method (TDEM) proposed by Volk and Hora [18]. The used material for the experimental investigations is an uncoated micro-alloyed steel HC340LA as in [1]. The experimental setup can be found in Figure 3. For controlling the strain path the mean major and mean minor strain inside the evaluation area are used. The deviation of the strains inside the evaluation area is neglected. It is also possible to control the strain path by measuring the strains only on single facets, but as sometimes deviations occur, the use of the mean values is chosen. The communication between the different computers the TCP/IP-protocol is used. Both the LabView™ and the testXpert™ software have a TCP/IP interface which can be used.

3. Results and discussion
The database needed for the adjustment of the draw beads was created by conducting various experiments. Several different draw bead heights were tested in order to determine which draw bead height leads to which strain ratio \( \beta = \varphi_2 / \varphi_1 \), see Figure 4. Also, bi-linear experiments were conducted to quantify the influence of the biaxial pre-forming as well as the influence of the strain history on a consecutive forming step.
In the experimental setup, a hemispherical Nakajima punch is used. As a result of this setup, a biaxial pre-strain at the beginning of the experiment occurs which is clearly visible in Figure 4. This pre-strain affects the strain paths with a negative strain ratio the most. The biaxial pre-forming has to be taken into account for the first forming step. All following forming steps do not show a biaxial pre-forming. Therefore, lower strain ratios are possible in the consecutive forming steps shown in Figure 5. The shown database in Figure 4 is hence not valid for bi- or multi-linear experiments. A different database for bi-linear experiments has to be implemented in the LabView™ tool. The strain paths with a positive strain ratio $\beta$ are not significantly affected as the biaxial pre-forming does not affect the strain paths as much as negative strain ratios.

![Figure 5. Influence of a consecutive forming step on the strain ratio in the uniaxial load case.](image)

The draw bead height adjustment can only be done between the forming steps when the clamping force is removed. Removing the clamping force and the heading back of the punch leads to a relaxation of the specimen. The following reduction of the major and minor strain can be clearly seen. The resulting springback is approximately 0.01 in major strain, see Figure 6. This springback value is almost constant for all strain ratios $\beta$. Hence, a constant correction value is taken into account in the control loop.

![Figure 6. Strain path for a three-step experiment. Arrows indicate the start of the next forming step.](image)

For some strain path combinations, the draw bead height has to be reduced. For example, a plane strain increment with a draw bead height of 7 mm and 3.5 mm respectively is followed by a uniaxial strain increment with a draw bead height of 7 mm and 0 mm respectively. Therefore, the specimen is rotated by 45° in the tool, see Figure 7 (a). The movement of the tool which applies the clamping force is used to remove the draw beads (Figure 7 (b)). This procedure does affect the material in the draw bead zone. Nevertheless, during the conducted experiments with and without multiple strain path changes, no failure of the specimens in this area has occurred.

![Figure 7. Removing of the draw beads, (a) Rotating the specimen by 45°, (b) draw bead height before removing, (c) draw bead height after removing.](image)
To ensure a sufficient measuring frequency of the strains a limited evaluation area has to be chosen. The laser–welded cruciform specimen has a small area with a reduced thickness (d = 12 mm), see Figure 1. If the in-line strain measurement and calculation is done in this area, a frequency of 8 Hz can be reached. As this frequency is close to the suggested measuring frequency of 10 Hz in the DIN ISO 12004-2, a sufficient measuring frequency is ensured.

The control loop allows therefore the creation of accurate non-proportional load paths, see Figure 8. A big advantage of the presented approach is, that in comparison to the used method in [1] also small strain increments are feasible. This is possible due to the fact that with the new approach the strains are measured in-line during the experiment and the relaxation of the specimen is taken into account. This relaxation leads to a decrease in the dome height of the formed specimen. Also, the strain increase with increasing punch height is not linear. At higher strains, only a small increase in punch height can lead to a significant increased strain. Thus, the punch height is not a sufficient parameter to create accurate strain increments. As the measured and calculated strains during the experiment are directly transferred to the LabView™ tool, the strain path of the experiment can directly be extracted from the software. For the last forming step before failure no in-line measurement is used to ensure a frame rate of 10 frames per second as stated in the ISO12004-2.

![Figure 8. Comparison of given strain path to the measured strain path](image)

At the beginning of the experiment a deviation between the given and the measured strain path is detectable. This is due to the biaxial pre-forming of the specimen. An adaption of the draw bead height does not lead to a more accurate strain path. As for the last forming step, no adaption of the strain path is done, the strain path shows a significant deviation which is also due to the non-linearity of the strain path after the onset of diffuse necking. This non-linearity is also occurring for linear strain paths, see Figure 4. Nevertheless, the creation of defined non-proportional load paths is possible. The onset of necking for the conducted multi-linear experiments can accurately be predicted by the Generalized Forming Limit Concept (GFLC) as proposed by Volk and Suh [7], shown in Figure 9.

![Figure 9. Different created strain paths by the semi-automatic approach and the predicted failure by the GFLC.](image)
4. Conclusions

With the presented in-line measurement almost arbitrary non-proportional loading paths can be created. Due to the limited evaluation area of the cruciform specimen a sufficient measuring frequency is possible. This allows to react on occurring deviations from a given strain path. Due to the hemispherical punch used in the experimental setup, a biaxial pre-strain occurs at the beginning of the experiments. The biaxial pre-forming does not occur in the following forming steps. This leads to the need of a second database for bi- and multi-linear strain paths. To be able to adjust the draw bead height after a strain increment, the clamping force has to be removed. This leads to a relaxation of the cruciform specimen. All those effects are taken into account by the presented semi-automatic approach. Nevertheless, this experimental setup presents an easy way to create non-proportional load paths. To predict the onset of necking for the conducted non-proportional load paths with several different forming increments, the GFLC-model is used. It is shown, that even strain paths with four different strain increments are predicted accurately.

Due to the use of the experimental setup using a passive draw bead tool to create the retention forces, some limitations are given. For certain strain increment combinations, for which the draw bead height has to be lowered, the beadings have to be removed and formed again. By using active actors this problem can be solved. Also by using active actors, the specimens would not have to be relaxed between the forming steps while adjusting the retention forces.

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