Experimental evaluation of Bauschinger effects during tension-compression in-plane deformation of sheet materials

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Abstract

An experimental analysis of the effect of in-plane strain path changes and Bauschinger effects during mechanical loading that involves compression is quite challenging for sheet materials because they are prone to buckling. In this paper, we present a newly developed method that allows to deform sheet metals in tension and in compression. Our experimental setup primarily consists of an anti-buckling clamping device that can be used in a universal mechanical testing machine. Surface strains are measured with a digital image correlation (DIC) system. To demonstrate the viability of our method, first tests are conducted on thin sheet specimens (1 mm thickness) of a DC06 steel. Several approaches to reduce friction between the clamping system and the specimen are investigated. The validity of the test results is established in monotonic tensile tests. Measurements with different amounts of maximum tensile strain and reversed strain values are also discussed, showing that the material exhibits a Bauschinger effect, which is further quantified using different Bauschinger parameters.

1. Introduction

The decrease of the yield strength after a load path change is known as Bauschinger effect [1]. To quantify the Bauschinger effect as a function of different amounts of maximum (previous) strain, various parameters (Bauschinger effect parameter, Bauschinger strain, Bauschinger strain parameter) have been proposed, see e.g. [2-4]. Those parameters can be determined in experiments with load path changes. Relatively simple experiments with load path changes are shear tests with a reversal of shear direction [5, 6] or tensile tests with subsequent compression tests [2, 7]. Compared to the established tension-compression testing of bulk materials [8-11], tension-compression testing of sheet materials is challenging: sheet materials are prone to buckling under compressive loading. To overcome this issue, comb-shaped devices are often used; these devices provide additional support from the sides of the sample to prevent buckling (see also figure 1d for an example of a comb geometry). Kuwabara et al. developed such supporting clamps. They used a conventional specimen and measured forces with a load cell and strains with a strain gage, but their experimental approach required the design of a dedicated load frame [12]. Tan et al. and Boger et al. suggested to use a custom-designed, non-standard dog bone specimen, hydraulic clamps and strain gages for strain measurements [13, 14]. To determine forces, they performed calculations to account for friction in the experimental setup, using experimental friction values from [15].
Piao et al. used a similar setup, but with an additional option to heat the clamps [16], and Lee et al. used a similar rig like Kuwabara with slightly different combs and also with the heated clamps. For strain measurements they used a laser extensometer [17]. Knoerr et al. employed special clamps fixed with springs on non-standardized specimens. They performed (out of plane) strain measurements using digital image correlation (DIC) [18]. These previous studies provided a useful basis for the development of our own experimental setup, which we built in the light of previous approaches (and the corresponding issues and limitations), and considering the following requirements: The experimental setup should

- allow for continuous, uninterrupted tension and compression cycling
- facilitate the use of standard specimens
- fit into a conventional universal tensile testing machine
- allow for direct, in-plane strain measurements.

This paper primarily reports on the development of our experimental setup dedicated to tension-compression testing. Moreover, with this new setup, tension-compression-tests were performed on steel sheet material. We compare the test results with those of conventional monotonic tensile tests. Measurements with different amounts of prestrain and reversed strain values are also discussed, showing that the material exhibits a Bauschinger effect. The magnitude of the Bauschinger effect is finally evaluated using different Bauschinger parameters, and compared to bulk material data.

2. Experimental

In all experiments presented in this paper, a steel sheet material with a thickness of 1 mm was used. The steel is a low-carbon, interstitial free DC06 with 0.02 wt.-% C, 0.25 wt.-% Mn and 0.3 wt.-% Ti and Nb. This alloy was chosen as simple reference materials because the low amount of alloying elements allows to exclude further effects associated with the formation of precipitates, additional heat treatments or impurities.

2.1 Development of a new experimental setup for tension-compression testing

Figure 1 shows the new experimental setup for tension-compression testing that was developed to meet all requirements listed above. The setup consists of clamps (to hold the sample) and of four moveable, comb-shaped parts (which restrict out of plane deformation). This setup is installed between a die set that is adapted to fit into a conventional testing machine (ZWICK/ROELL Zmart Pro Universal 100 kN), figure 1a. A standardized specimen (following the regulations of [19]) with a gauge length of 50 mm and a width of 12.5 mm is placed between the two front parts and the two back parts, figure 1b. The comb-shaped clamps prevent buckling. For strain measurements, a DIC system is used, figure 1b. Because of the thickness of the clamps (16 mm, to ensure a high stiffness), proper illumination of the sample surface, which is visible between the comb-shaped fingers, a ring light is installed around the DIC camera, figure 1c. This results in excellent illumination without any shadows on the surface of the specimen that is painted with speckle patterns, figure 1d. During the experiment, the DIC system tracks the displacements of small regions on the sample surface, and thus allows for accurate, local measurements of surface strains.
Figure 1: Tension-compression setup with comb-shaped fingers (a) installed between a die set in a standard testing machine. The standardized tensile specimen is placed between the two front and the two back parts of the tool (b). For sufficient illumination between the combs’ fingers, a ring light is placed around the DIC camera (c); the illuminated surface of the specimen contains speckle patterns for DIC measurements (d).

While the new setup in principle meets our design criteria, certain issues arise during application: on one hand, friction occurs between the clamps and the specimen, and this effect cannot simply be neglected; on the other hand, even when friction is minimized by appropriate experimental measures, the force data cannot be used directly to calculate stresses (and thus material strength values). One typical approach is to perform complementary FEM simulations to account for friction in the setup (see [14, 16, 18]), but because this approach is tedious, one goal of our study was to accurately determine stresses without additional simulations. Below, we describe strategies that allow to conveniently handle these challenges.

2.2 Reducing friction in the experimental setup

The issue of friction is quite common (and most challenging) in tension-compression testing. When no special measures are taken to reduce friction, one frequently observes strain localization: the specimen is then primarily deformed in the zone near the “fingers” of the comb-shaped clamps. For a given nominal strain, this effect ultimately leads to higher stresses compared to conventional tests. This is obvious from the stress-strain curves presented in figure 2, where we compare the benchmark curve measured without the comb-shaped clamps with an experiment with clamps (but without trying to reduce friction: curve labeled “with clamps only”) and with experiments where different attempts were made to reduce friction. The common approach to reduce friction is to place Teflon (PTFE) sheets between the specimen and the anti-buckling device to reduce friction [12-14, 16-18]. We observed, however, that this approach is not sufficient when applied to our experimental setup: putting PTFE foil on one or both sides of the sample, and even combining PTFE foil and PTFE spray, does reduce friction, but the corresponding stress-strain curves still do not agree very well with the reference measurement.
Figure 2: Force-strain-curves determined while using different methods to reduce friction in the experimental setup. The benchmark is the curve “without clamps”. The measurement without any reduction of friction (“with clamps only”) exhibits the strongest deviations. Compared to the results of the literature, none of the methods using Teflon is in sufficiently good agreement with the benchmark measurement.

To improve on these first results, we also tried applying other lubricants used commonly in metal forming, such as Beruforge (produced by Bechem Lubrication Technology) or MoS2, but this also did not work. Knoerr et al. suggest the use of springs to press on the anti-buckling device [18], but in our experimental setup, this method lead to large variation in the resulting force-strain-curves, especially at the point of load path change (i.e., at maximum strain, prior to load reversal).

We finally came up with a new idea to prevent friction by machining a notch in sheet thickness (1 mm) into the clamps, figure 3. This allows the specimen to move freely and without additional friction during the initial tensile deformation. Despite this increased degree of freedom, after the load path change (and during subsequent compressive loading) the clamps immediately and effectively avoid buckling. The stress-strain curves in figure 4 demonstrate that this approach is quite effective: there is a very good agreement between tests performed with and without the modified clamps.
Figure 3: A successful strategy to considerably reduce friction in our tension-compression device is to machine a notch in sheet thickness (1 mm) into the clamps (shown schematically on the left). The photograph on the right shows the pair of clamps with the machined notch.

Figure 4: The comparison between four different samples demonstrates that machining a notch in the clamps is an effective method to reduce friction: there is very good agreement between samples tested without clamps (as a reference) and those with clamps with the machined notch. Both at the yield point and at strains up to 6%, all curves agree very well.

2.3 Measuring forces and determining accurate material strength data
In all experiments reported here, forces are measured using the load cell of the conventional testing machine. The clamping device is installed in this testing machine between a die set, see also figure 1a. Unfortunately, this die set is also subjected to internal friction, which results in increased force values, and thus in artificial “residual stresses” when data from the load cell are used to calculate stresses. One option to measure those “residual stresses” is to perform an additional measurement after the sample has been removed, using only the empty setup after each test, and following the same machine path. Figure 5 shows...
forces as a function of nominal strain during measurements without samples for strain paths with four different maximum strains. These forces, which simply result from internal friction, are not constant, but in all measurements they are in a similar range. The measured strain values are much higher than the maximum strains during the actual tension-compression tests because strains are measured on the clamps and no material resists the deformation. We also note that forces under tensile load are lower than the corresponding forces under compression. This indicates that the internal friction of the experimental setup is higher under compressive loads. Such calibration measurements were performed after each tension-compression test, and the “residual stresses” were then subtracted from the stresses measured in the actual tension-compression test. This procedure results in stress-strain curves that agree very well with data from conventional tensile tests (i.e., using a standardized sample shape in a uniaxial testing machine, and no special experimental setup) performed on the same material.

![Figure 5](image)

**Figure 5:** Force-strain curves measured with the empty drives for different maximum strains. Force values in tension are lower than forces under compression. These force data are used to determine accurate stress data from the actual experiments.

### 3. Results and Discussion

While the first part of this paper (and in particular the two preceding sections) have been focused on establishing and validating a detailed testing protocol for our new experimental setup for tension-compression testing of thin sheet materials, we now present first results (on the DC06 sheet material) that were obtained following our experimental procedure. In figure 6, our first results of tension-compression tests using maximum strains of 0.5, 1, 1.5, and 2 %, respectively, are shown. Note that the loading parts of all stress-strain curves fall on top of each other – this demonstrates that our experimental setup provides reproducible as well as reliable (as demonstrated by comparing to conventional tensile data) results. The yield strength of all samples in tension is 122 MPa, which is also in excellent agreement with the conventional tensile test. Note that, in all cases, the stress at the onset of plastic deformation after load
reversal is lower than the maximum tensile stress prior to load reduction: the material clearly exhibits a Bauschinger effect. Furthermore, we observe that the flow curve after load reversal does not exhibit a distinct point separating the elastic from the plastic region. Therefore, the yield strength under compression load cannot be determined exactly. Tan et al. observed the same phenomenon [13]; we follow their suggestion to use $R_{p0.2}$ as a reasonable approximation for the yield strength under compression.

![Stress-strain curves of tension-compression experiments with different maximum tensile strains (0.5, 1, 1.5, and 2 %). The yield strength under tensile load (122 MPa) agrees well with data from conventional tests. After load reversal, all specimens exhibit reduced yield strengths under compression.](image)

**Figure 6:** Stress-strain curves of tension-compression experiments with different maximum tensile strains (0.5, 1, 1.5, and 2 %). The yield strength under tensile load (122 MPa) agrees well with data from conventional tests. After load reversal, all specimens exhibit reduced yield strengths under compression.

Different parameters have been proposed to quantify the Bauschinger effect. In [3, 4]), a Bauschinger effect Factor was introduced. This factor, $\alpha$, is defined as the ratio between the yield strength after load reversal (i.e., in compression) $\sigma_R$ and the maximum tensile stress $\sigma_F$, figure 7. Abel and Muir proposed two parameters that are focused on strain values: The first one is the Bauschinger strain $\beta$ [2] which can be described as the strain that is necessary (after load reversal) to reach the same stress as the maximum tensile stress prior to load removal, figure 7. The second parameter is the Bauschinger strain parameter $\beta_e$ [2]. This parameter is defined as the ratio between the Bauschinger strain $\beta$ and the maximum tensile strain $\varepsilon_p$, figure 7.
Figure 7: Schematic representation of a stress-strain curve of a tension-compression test (compressive stresses multiplied by -1 for better illustration). The specimen is deformed up to a maximum tensile strain $\varepsilon_p$, and a maximum stress $\sigma_F$, respectively. Then the load is reduced and reversed so that the sample is loaded in compression. The material’s subsequent yield strength in compression is $\sigma_R$. The Bauschinger effect factor $\alpha$ is defined as the ratio between $\sigma_R$ and $\sigma_F$. The Bauschinger strain $\beta$ corresponds to the strain that, after load reversal, is necessary to reach the same stress as at load removal. The Bauschinger strain parameter $\beta_e$ is the ratio between Bauschinger strain $\beta$ and maximum tensile strain $\varepsilon_p$.

To quantify the Bauschinger effect in the DC06 tested here, for a direct comparison with data from the literature, and as a first step towards further research on Bauschinger effects during multi-axial deformation, we calculated the different Bauschinger parameters as a function of different maximum tensile strains, figure 8. The Bauschinger effect factor $\alpha$ (which, like all Bauschinger factors discussed here, would be equal to 1.0 in the absence of a Bauschinger effect) decreases slightly with increasing maximum tensile strain: for a maximum strain of 0.5, $\alpha$ is 0.91; for a maximum strain of 2 %, $\alpha$ is 0.82. This trend of the Bauschinger effect factor has also been observed for different sheet [15] and bulk materials [3].

In contrast, the Bauschinger strain $\beta$ increases with increasing tensile strain: for 0.5 %, $\beta$ is 0.56, and for 2 %, $\beta$ is 1.18. Again, this is in excellent agreement with results on bulk material with a similar chemical composition reported in [2]. Finally, when we consider the ratio between Bauschinger strain $\beta$ and the maximum tensile $\varepsilon_p$ (which is the so called Bauschinger strain parameter $\beta_e$) one interesting result is that, for 0.5 %, $\beta_e$ is higher than 1. This demonstrates that a higher strain after load reversal is necessary to reach the same (absolute) stress value as at load reversal. Abel and Muir observed the same effect for bulk
material [2], but only for small tensile strains. At higher strains, \( \beta_e \) decreases rapidly: for 1 %, \( \beta_e \) is 0.76, for 1.5 % it is reduced to 0.66, and for 2 % it is 0.58. This observation also agrees well with [2].

Figure 8: Evolution of the different Bauschinger parameters as a function of maximum tensile strain.

4. Summary and Conclusions

This investigation focused on the development of a new experimental setup for in-plane tension-compression deformation of sheet metals. Our design meets several requirements; it (i) allows using a conventional/standardized specimen, (ii) can be directly used for testing in a conventional testing machine and (iii) is designed for in-plane strain measurements with digital image correlation. One key issue for tension-compression tests is friction between parts of the setup and the specimens. This issue was successfully tackled by machining a notch in sheet thickness into the clamps. Moreover, we discussed how the amount of friction in the die set can be determined by performing empty runs after the mechanical tests themselves. By subtracting the characteristic force values from the measured forces during the tension-compression experiments, stress-strain curves that are in very good agreement with data from conventional tensile tests can be obtained. Using our optimized experimental setup, we performed first investigations on samples of a DC06 steel, and we discussed the evolution of different parameters that allow quantification of the Bauschinger effect as a function of different maximum tensile strains. Our experimental results show that the steel sheet DC06 clearly exhibits a Bauschinger effect, and they fully agree with literature data on bulk material with a similar chemical composition.

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