Investigation of the influence of loading direction after pre-forming on the formability and mechanical properties of DP600

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Abstract. The material behaviour after non-proportional strain paths is subject of numerous current investigations. These investigations show that in addition to the stress state, a change in the direction of loading also has a significant influence on the material behaviour. In this work, the influence of non-proportional strain paths on the mechanical properties such as tensile strength, uniform strain, elongation at fracture and yield strength as well as the influence on formability is determined. For this purpose, a dual-phase steel CR330Y590-DP, with a thickness of 0.8 mm, is investigated in more detail. The material is pre-strained to different strain values and then further examined with Nakajima and tensile tests. The influence of the loading direction is determined by five different post-strain directions (0°, 22,5°, 45°, 67.5°and 90°) to the initial pre-strain direction. In addition to the method according to the standard, the yield strength is determined by a temperature-dependent determination method, which is based on the thermoelastic effect. This method has already been qualified for simple uniaxial tensile tests and a relation to the microstructural behaviour was proven. Thus, it provides valuable conclusions on the microstructural behavior for the tests performed within this study with a change in the loading direction.

Introduction

Non-proportional load paths are being investigated for several years. Many researchers focus on the effect on the mechanical properties by using tensile or shear tests but also on the formability using Nakajima experiments. One of the most looked at materials are dual-phase steels with different strengths. By using shear tests, Hérault et al. [1] analysed the influence of uniaxial pre-strain on the elasto-plastic behavior. To describe the material behavior using the Homogeneous Anisotropic Hardening model (HAH-model), experiments with a pre-forming level of at least $\varepsilon = 2\%$ are required due to the significant material behaviour evolution below that level. Larsson et al. [2] investigated the influence of pre-forming height and a change in loading direction on Docol 600DP and Docol 1200DP using tensile and shear tests with pre-formed material. The pre-forming height, as well as a change in loading direction not only influence the onset of yielding but also the formability in the tensile test experiments. A change in loading direction by 45° or 90° after a pre-forming of $\varepsilon = 10\%$ lead to a reduced formability. Liao et al. [3] used SEM, EBSD and TEM to investigate the microstructural effects of a proportional, pseudo cross and cross-loading in DP500, DP600 and DP800. For the experiments with a change in loading direction, yielding occurred at lower stress compared to the monotonic experiments. This effect is enhanced at higher pre-forming levels. The evolution of texture was found to be weak for all three DP-steels and cannot explain the effects on the mechanical properties. Nevertheless, the presence of a soft ferritic and a hard martensitic phase leads to a very inhomogeneous plastic deformation of the material. At the onset of yielding the soft and weakly strain hardened ferrite grains control the mechanical behaviour. For a DP800 the effect on the onset of yielding takes place already at very low strains of $\varepsilon = 1\%$ and increases as the pre-forming height reaches higher levels [4]. This effect was also captured by other researchers [5]. Yu and Shen [6] looked at various pre-forming states for a DP590. They investigated the influence of a uniaxial, plane-strain and equi-biaxial pre-forming state on the tensile test results. The pre-forming state also influences the mechanical properties. The Young's – modulus is reduced with increasing pre-forming height, where the equi-biaxial pre-forming state lead to the strongest decrease.

The aim of this study is to determine the influence of three different plane-strain pre-forming levels and three different post-loading directions on the mechanical properties using tensile tests. The influence of the pre-forming on the formability will be examined by standard Nakajima experiments. The experiments in this paper are conducted with a CR330Y590-DP (DP600) steel with an initial thickness of 0.8 mm.

Experimental Procedure

The pre-forming of the material took place on a hydraulic Dieffenbacher press in combination with a modified Marciniak-tool developed by Weinschenk and Volk [7]. To ensure a homogenous plane-strain pre-forming, the specimen geometry was adapted from prior investigations [8,9] and was optimized for the used DP600 steel. The change in loading direction is obtained by a rotation of the tensile test and Nakajima specimens. For the tensile tests, five tensile test samples can be manufactured from one single pre-formed specimen, while for the Nakajima experiments only one specimen can be extracted. All pre-forming specimens are cut out under 0° to the initial rolling direction, see Fig. 1.

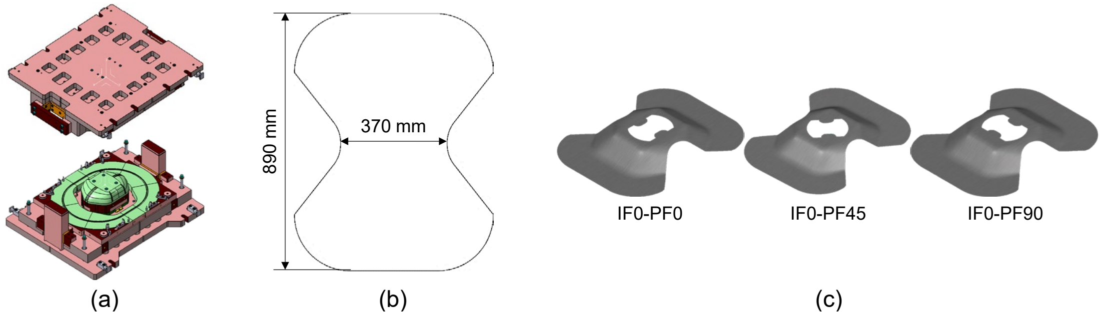


Fig. 1. (a) The used modified Marciniak tool, (b) Specimen geometry used for the plane-strain pre-forming. (s) Specimen extraction and nomenclature of the cut-out specimens.

For the tensile tests specimens according to DIN 50125 – geometry H with a width of 12.5 mm are used. The strain measurement is done by a laser extensometer with a gauge length of 50 mm and a constant strain rate of 0.001 1/s. To determine the onset of yielding, the temperature based method according to Vitzthum et al. [10] was employed. This method makes use of the thermo-elastic effect where the temperature decreases during the elastic deformation and increases during the plastic deformation. A closer description of the method can be found in [10].

The Nakajima experiments are carried out on a BUP1000 in combination with an Aramis 4M DIC system. The punch speed was set to 1 mm/s and a measuring frequency of the DIC-System of 10 Hz is applied. To minimize the friction between the punch and the specimen a PVC-pad with lubricant is used. To assess the onset of necking the Time Dependent Evaluation Method (TDEM) proposed by Volk and Hora [11] is applied. Four different Nakajima specimens are tested, ranging from 30 mm for the uniaxial strain state to 235 mm for the biaxial strain state.

Experimental Results

The results of the experiments with the initial material show a low dependency of the loading direction on the stress-strain curves (Fig. 2) as well as the forming limit curves (Fig. 7). All investigated directions differ only marginally. This changes for the pre-formed experiments. The influence of a change in loading direction can clearly be seen. At a pre-forming level of $\varepsilon_{v.Mises}$ = 0.066 and $\varepsilon_{v.Mises}$ = 0.097 specimens with a change in loading direction of 45° show the lowest fracture strain, while the elastic-plastic transition is different for all specimens with a change in loading direction. This effect increases for higher pre-forming levels. At a pre-forming level of $\varepsilon_{v.Mises} = 0.121$ the fracture elongation of the specimen with a change in loading direction is almost the same.

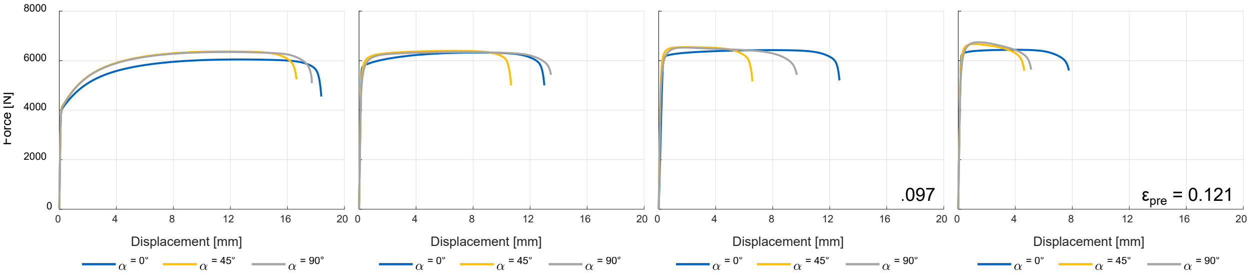
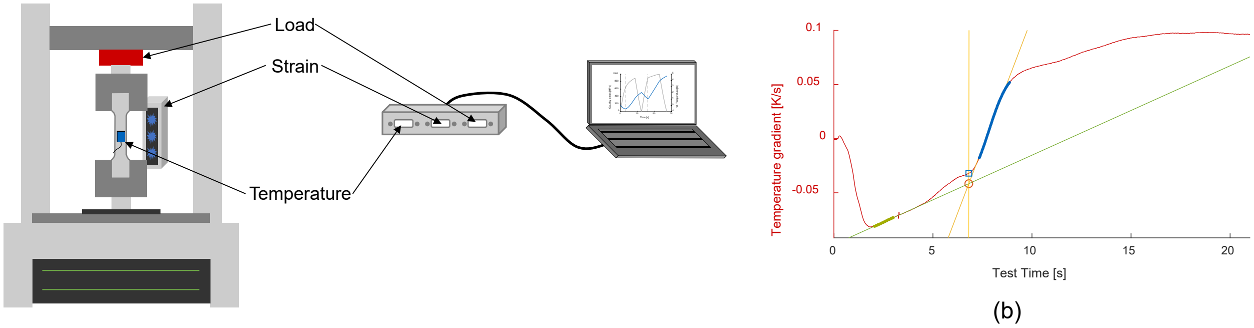


Fig. 2. Force-Displacement curves of the initial material and the three investigated pre-forming heights.

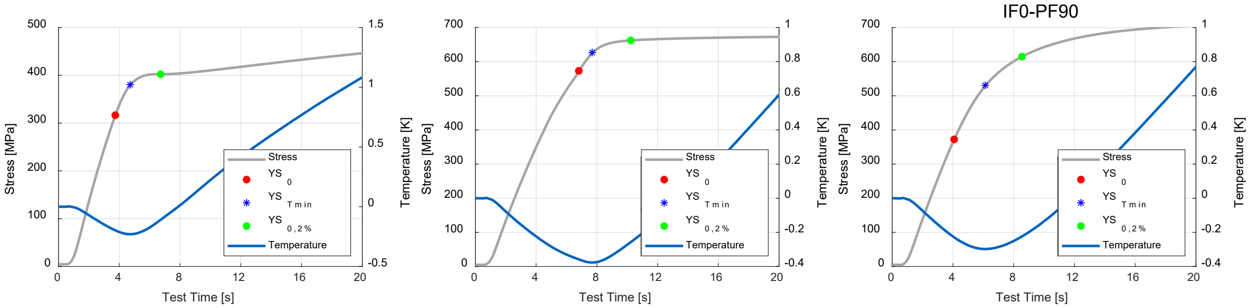
As many researchers have found a significant influence of the pre-forming and a change in loading direction on the elastic-plastic transition, the onset of yielding is further examined. To determine the onset of yielding, three different methods are employed. Next to the classic $R_{p0,2\%}$, depicted as $YS_{0.2\%}$ two temperature based methods are also applied. The temperature is measured throughout the experiment using a PT1000 thermometer, see Fig. 3 (a). The onset of yielding was then determined at the temperature minimum (YS_{Tmin}) and at zero plastic strain (YS_0). YS_0 is calculated by fitting two regression lines into the first derivative of the temperature signal, see Fig. 3 (b). One line is fitted into the elastic region where the temperature is decreasing while the other line is fitted into the area around the temperature minimum where the derivative is zero. The onset of yielding is then determined at the intersection of the two lines and via an angle bisector. A closer description of this method can be found in Vitzthum et al. [10].



(b)

Fig. 3. (a) Experimental setup using the thermometer, (b) Determination of YS0 using the temperature derivative.

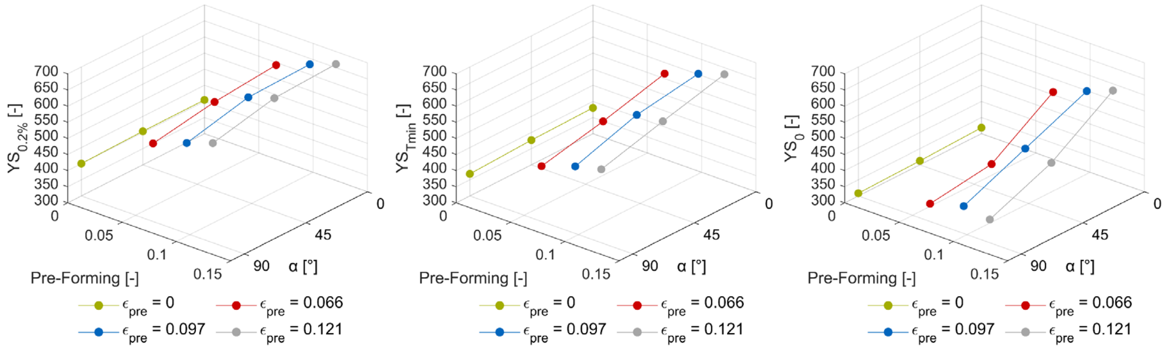
The onset of yielding is strongly dependent on a change in loading direction and the pre-forming level. The higher the pre-forming level, and when there is no change in loading direction, the closer the onset of yielding assessed by the three different methods is moving together. As soon as there is a change in loading direction, the temperature signal changes significantly. While specimens with no change in loading direction show a sharp temperature signal, almost like a V-shape, the specimens with a change in loading direction have a round temperature signal, almost like an U-shape, shown in Fig. 4.



(c)

Fig. 4. (a) Onset of yielding for an initial specimen in 0° to the rolling direction, (b) Pre-formed specimen with no change in loading direction (IF0-PF0), (c) Pre-formed specimen with a change in loading direction by 90° (IF0-PF90).

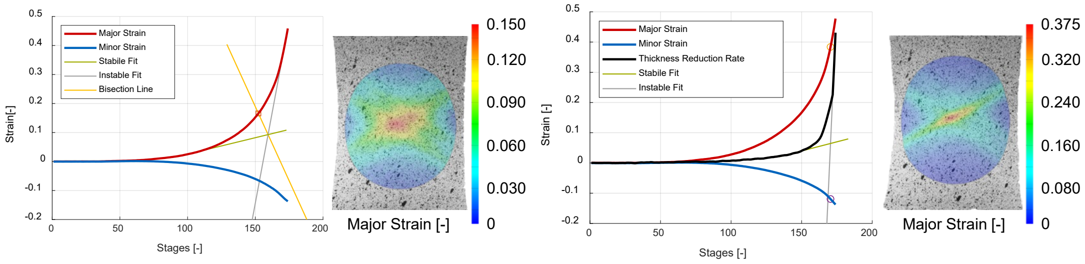
Looking at all results for the different angles and pre-forming heights, it can be seen, that the onset of yielding for the $YS_{0.2\%}$ method is steadily increasing with increasing pre-forming level almost untouched by a change in loading direction, see Fig. 5 (a). The temperature-based results however, show a strong dependency on a change in loading direction as soon as a pre-forming took place, Fig. 5 (b) and (c). These results indicate that when a change in loading direction occurs after a pre-forming, some grains start to yield a lot earlier than others do. This leads to the smooth and round temperature signal. While the grains of specimens with no change in loading direction yield almost at the same time, leading to this sharp V-like shape. This effect is more substantial, the higher the pre-forming level is.



(a) (b) (c)

Fig. 5. Results for the $YS_{0.2\%}$ method (a), (b) for the temperature minimum and (c) for the YS0-method.

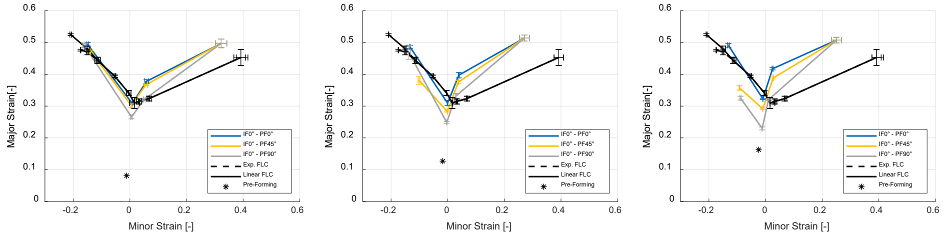
In the Nakajima experiments, for high pre-forming levels and a change in loading direction, shear failure is observed. When using the Time Dependent Evaluation Method (TDEM-method) a significant overestimation of the formability for such specimens is found, shown in Fig. **6** (b). The evaluation of specimens with such a shear failure is performed by a modified TDEM-method, see Fig. 6 (a), which was already used in [8]. In Fig. 6, the two methods are shown for a 30 mm wide specimen with a change in loading direction of 45° (IF0-PF45) and a pre-forming level of $\varepsilon_{pre} = 0.193$.



(a) (b)

Fig. 6. (a) Method used in Volk et al. [8] for Shear-Failure, (b) Time Dependent Evaluation Method [11].

The higher the pre-forming level, the more a change in loading direction influences the formability, see Fig. **7**. For the pre-forming level with $\varepsilon_{pre} = 0.151$, the IF0-PF45 specimens show the lowest formability, this is different to the results for the HC340LAD [8]. The most severe influence was observed on the plane-strain post-forming and a change in loading direction by 90° (IF0-PF90) after a pre-forming of $\varepsilon_{pre} = 0.193$. Here, almost instant necking occurs.

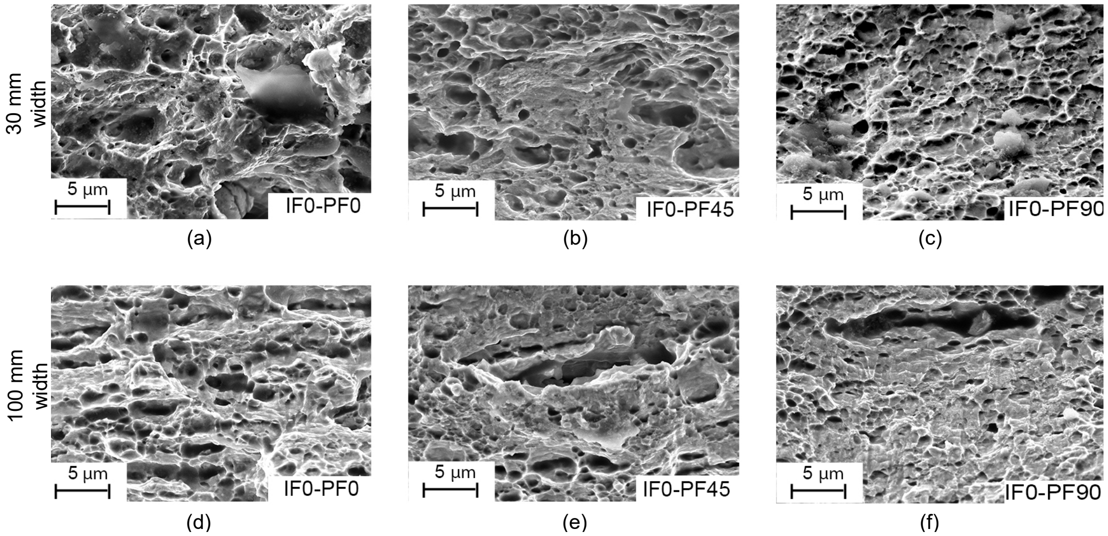


(a) (b) (c)

Fig. 7. (a) Forming Limit Curves for $\varepsilon_{pre} = 0.097$, (b) Forming Limit Curves for $\varepsilon_{pre} = 0.151$ (c) Forming Limit Curves for $\varepsilon_{pre} = 0.193$.

In comparison to the results for the micro-alloyed steel HC340LAD and the aluminium alloy AA6016-T4, the effect of a change in loading direction is somewhere in between. The HC340LAD showed a stronger dependency on the formability, see [8], while the AA6016-T4 showed almost no influence of a change in loading direction on the formability [12].

One reason for such a dependency on a change in loading direction might be the presence of voids. Asik et al. [13] found, that void growth and nucleation for a DP600 steel already takes place before the uniform elongation is reached. These voids primarily occur at inclusions and at the ferrite-martensite interface but also martensite cracking leads to the creation of voids. Due to the banded structure of the martensite inside the ferritic matrix, the damaged area is dependent on the loading direction. Gerstein et al. [14] investigated the voids after deformation of a DP600 using SEM – microscopy. Voids caused by plastic deformation have shown an elongated shape in the direction of loading. By using in-situ X-Ray microtomography Maire et al. [15] also found, that the biggest cavities in tensile test showed an elongated shape in the direction of loading. If the stress state has a higher triaxiality than that in the tensile test, the cavities are likely to become more isotropic. As the pre-forming state in this study is plane-strain, the voids might show that elongated appearance in the direction of the first loading step. This could explain the anisotropic damage behaviour in the Nakajima experiments for specimens with a change in loading direction. In Fig. 8 the different fracture surfaces are shown. While the specimens with no change in loading direction (Fig. 8 a and d) show a ductile fracture with many small voids, the 30 mm wide specimens with a change in loading direction show almost a brittle fracture surface (Fig. 8 b and c). The number of voids is significantly reduced, compared to (Fig. 8 a). This can explain the reduced formability of the material as the ductility is reduced after a change in loading direction. For the plane-strain specimens with a width of 100 mm a different behaviour is observed. While the specimens with no change in loading direction (Fig. 8 d) show again a ductile fracture surface with many small voids, the specimens with a change in loading direction have considerably big voids caused by hard martensitic inclusions which can be seen in the big void in (Fig. 8 f). In between the vast voids, a shear behaviour is found where the big voids started to coalescence. The increased void growth and the coalescence of the voids could lead to the significant reduction in formability.



(a) (b) (c)

(d) (e) (f)

Fig. 8. SEM-images for two different specimen widths (30 mm and 100 mm) and the three investigated post-loading directions IF0-PF0 (a,d), IF0-PF45 (b,e) and IF0-PF90 (c,f) for the pre-forming height of $\varepsilon_{pre} = 0.193$.

Summary

In this paper, the influence of a plane-strain preforming at different levels as well as a change in loading direction has been investigated. By using tensile and Nakajima tests, the impact on the mechanical properties like yield strength and fracture elongation as well as the Forming Limit Curve has been quantified. It is found, that a change in loading direction strongly affects the onset of yielding in tensile test by using temperature-based methods. This effect is not captured by using the classical $YS_{0.2\%}$ method. This might be caused by the fact that some grain orientations start to yield earlier than others and therefore lead to a continuous increase in temperature and a U-shaped temperature signal. For specimens with no change in loading direction no such effect is observed. In fact, the two temperature-based methods, temperature minimum YS_{Tmin} and yield strength at zero strain YS_0, are moving closer together. This indicates that the grains with different orientations almost yield at the same time, leading to a sharp elastic-plastic transition.

For the Nakajima experiments, a strong effect on the formability after a certain level of pre-forming is noticed. Especially on the left-hand side of the Forming Limit Curve, this influence was determined. As some of the specimens, mostly those with a significant loss of formability did not show a ductile necking failure but instead a shear failure, the Time Dependent Evaluation Method (TDEM-method) was not applicable. To determine the limit strains for those specimens, the same procedure as for the TDEM-method, but instead of the thickness reduction rate $\dot{\varphi}_3$ the Major Strain is used to fit the two regression lines. This method showed better results in comparison to the TDEM-method, which overestimates the limit strains for shear failure specimens.

As voids caused by the pre-forming process might be the cause for this anisotropic behaviour, SEM-microscopy will be carried out with the pre-formed material in order to detect voids inside the material. In addition, the disposal of the voids is of interest as some researchers found that voids are aligned in certain directions.

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