

Influence of hydrogen on formability and bendability of DP1180 steel for car body application

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Abstract. In order to reach future light weight targets, it is increasing necessary to use advanced high strength steels with tensile strength 980 MPa or higher in automotive body-in-white structures. Due to the sensitivity to hydrogen embrittlement and the limited understanding of various aspects of hydrogen embrittlement on processing and function, the wide application of these steels is still limited.

In the current work, the influence of hydrogen on the multiaxial forming behavior was investigated by determining the forming limit curve and bending limit curve of DP1180 steel. Hydrogen concentration in the material was modified by cathodic charging. Then Nakajima tests on hydrogen uncharged and pre-charged samples were carried out in order to adjust and study different strain states resulting in the forming limit curve. In the study of bending limit curve, the steel sheets were pre-strained by Marciniak test. Bending load on the uncharged and pre-charged samples was introduced by VDA238-100 bending tests. The experimental results indicated that the presence of hydrogen affected the formability and bendability of DP1180 steel. A clear difference in the influence of hydrogen at different strain states was observed. When formed in a biaxial strain state via the Nakajima test, the material showed the highest degradation in formability. Moreover, the samples with biaxial pre-loading showed more degradation in bendability comparing to those pre-strained in plane strain and uni-axial paths. Fractography by scanning electron microscope gave evidence of hydrogen-induced cleavage fracture on pre-charged Nakajima samples. Thus this investigation improves the understanding of influences of hydrogen on forming processes and provides important evidence for further studies on HE susceptibility of AHSS for the application on car body constructions.

1. Introduction

Today the automotive industry is utilizing more high strength steels to enable lightweight construction. However, the wide application of Advanced High Strength Steels (AHSS) with tensile strength over 980 MPa is limited by their sensitivity to Hydrogen Embrittlement (HE). HE in steels is defined as a loss in ductility and resulting brittle fracture due to the introduction and diffusion of hydrogen in the steel [1]. It can take place during the automotive production process or in-service process, once the applied stress and hydrogen content reach the threshold value of the material. In general, the process of HE is due to the interaction between matrix and atomic hydrogen atoms on a very small scale, the combination of several individual modes probably contributes. So far, two of the mechanisms have



been widely accepted in the research field: the Hydrogen Enhanced De-cohesion (HEDE) mechanism [2, 3] and Hydrogen Enhanced Localized Plasticity (HELP) [4, 5] mechanism. The susceptibility to HE in AHSS was already reported in many publications. Nevertheless, the previous studies focused on the loss of mechanical properties in tensile tests and hydrogen induced cracking on deformed samples [6-9]. To understand the role of hydrogen in automotive production process, the impact of hydrogen on formability need to be further investigated.

Forming Limit Curve (FLC) is a most commonly used processing criterion, representing the maximal in-plane formability [10]. FLC describes the first occurrence of membrane instability, but neglects the effect of sheet bending [11]. To fully evaluate the forming behavior the Bending Limit Curve (BLC) is also needed. BLC enables the analysis of drawing operations with superimposed bending and describes the failure due to local shear zones [10-12].

In the present work, the effect of hydrogen on the FLC and BLC was studied. Nakajima tests with uncharged and pre-charged samples were carried out to determine the FLCs of DP1180 steel with different hydrogen concentrations. Impacts of hydrogen on forming limits in different strain states were compared. Fractography by Scanning Electron Microscope (SEM) model was used to determine the hydrogen-induced fractures in pre-charged samples via Nakajima tests. In the study of BLC, Marciniak tests were carried out to provide pre-strains in different strain paths. The pre-loaded samples were pre-charged with hydrogen and afterwards critical strains to bending fracture were studied by bending tests according to VDA 238-100. The results illustrated that the pre-strains in different strain paths lead to a different susceptibility to HE and the bendability degraded distinctly. Thus this work clarifies the influence of hydrogen on the formability and bendability in different strain states.

2. Material and experimental methods

2.1 Material

A commercial advanced high strength steel DP1180 was investigated. The steel sheets were cold rolled to reach a thickness of 1.5 mm. The micrographs of DP1180 by SEM, as shown in Figure 1, illustrate that the microstructure of DP1180 consists of ferrite and tempered martensite phases. In rolling direction the material has a yield strength of 1024 MPa and tensile strength of 1224 MPa. The elongation to fracture is 7.6%.

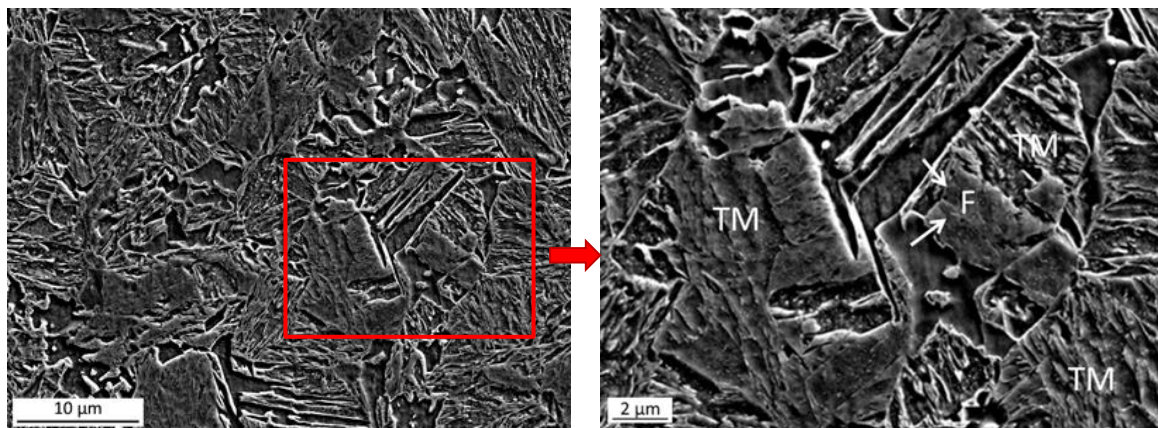


Figure 1. Micrographs of DP1180A in RD-TD plane, characterized by SEM, etched with 3% Nital.

2.2 Hydrogen charging and electro-galvanizing

Pre-charging was carried out to modify the hydrogen concentration in the steel. Figure 2 explains the preparation procedures. The samples for forming and bending tests were cleaned with an acid solution of 18% HCl with 3.5 g/l Hexamethylenetetramine for 10 s and subsequently with distilled water and acetone. The samples were pre-charged with hydrogen and electro-galvanized to prevent the effusion of hydrogen during forming/bending tests. The to-be-charged samples acted as a cathode.

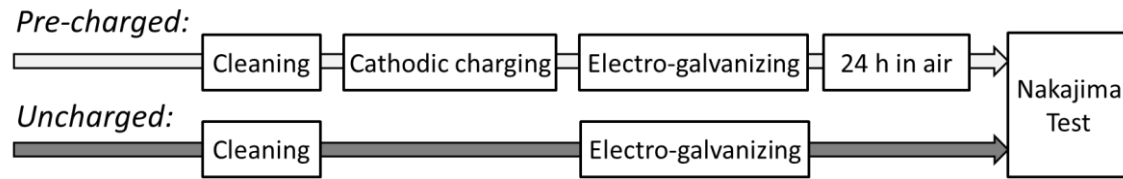


Figure 2. Preparation of pre-charged and uncharged samples.

The relevant parameters in pre-charging and electro-galvanizing processes are listed in Table 1. As reference, the uncharged samples were directly galvanized as same as the pre-charged samples.

Table 1. Parameters in pre-charging and electro-galvanizing processes.

Process	Samples for	Anode	Solution	Current density	Time
Pre-charging	Forming test	Pt-Ti net	3%NaCl+0.3% NH ₄ SCN	1 mA/cm ²	30 min
	Bending test				
Electro-galvanizing	Forming test	Zinc bar	ZnCl ₂	10 mA/cm ²	30 min
	Bending test			40 mA/cm ²	10 min

2.3 Determination of Forming Limit Curve (FLC)

Nakajima tests were carried out with three different sample geometries, as shown in Figure 3. On the surfaces of sample a characteristic stochastic black and white pattern was obtained by spraying. The Nakajima samples were drawn until failure, with a punch velocity of 2 mm/s. The patterns on the surfaces were recorded by a GOM ARAMIS system in a frequency of 10 pictures per second. The test was repeated five times.

The occurrence of necking was detected by analyzing the recorded pictures, according to the “linear best fit” method [13]. Five elements in the necking areas were selected, to calculate the mean values of the representative thinning rate in the last 20 pictures before fracture. In Figure 4 it is revealed that the representative thinning rate increases linearly with a low slope initially. After a transition period, it rises with a high slope. The intersection of the linear fitting curves in these two areas indicates the beginning of the instable necking during forming. The last picture number during stable deformation was found so that the strain distributions on the surfaces of sample, named forming limits, were determined.

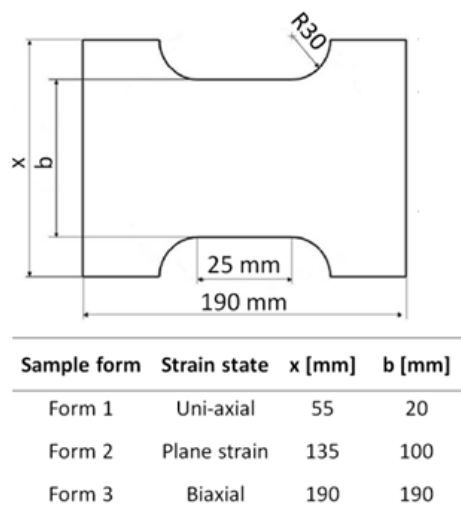


Figure 3. Sample geometries for Nakajima tests.

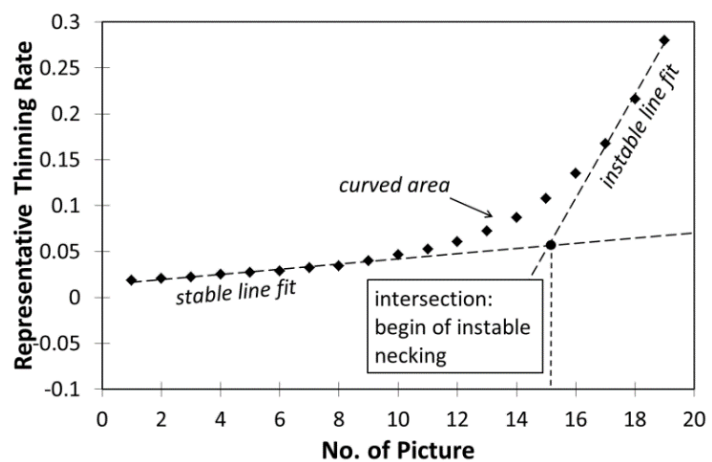


Figure 4. Detection of localized necking in a representative thinning rate diagram.

2.4 Determination of Bending Limit Curve (BLC)

BLC is a strain based criterion to predict failure under bending conditions. To determine the BLC of a material, a drawing operation for pre-straining and a superposed bending process are required [10, 11]. Figure 5 schematically describes the development of the BLC. In this study a Marciniak test with a punch diameter of 340 mm was applied to introduce the pre-straining in the steel sheets. The blank holder force was 400 kN and the punch velocity was 20 mm/s. The Marciniak samples were drawn in uniaxial, plane strain and biaxial strain states, until the maximal drawing depth was reached. Afterwards, bending samples with dimension of 60 mm×60 mm were cut from the Marciniak samples, and prepared by pre-charging and zinc coating.

Superimposed bending loads were applied by the three-point-bending test according to VDA 238-100. Figure 6 illustrates the schematic bending device. The radius of bending-sword punch was 0.4 mm. The samples were bent with a punch velocity of 20 mm/min. A force drop of 30 N was defined as the failure criterion in bending procedure (Figure 7). In each variant, five tests were repeated.

The strain distributions on the surfaces of Marciniak sample and bending sample were measured by optical metrology: the stochastic black and white patterns before and after deformation were recorded and analyzed by GOM ARAMIS system, in order to calculate the values of major and minor strains. Figure 8 shows the strain distribution on the bending edges [10].

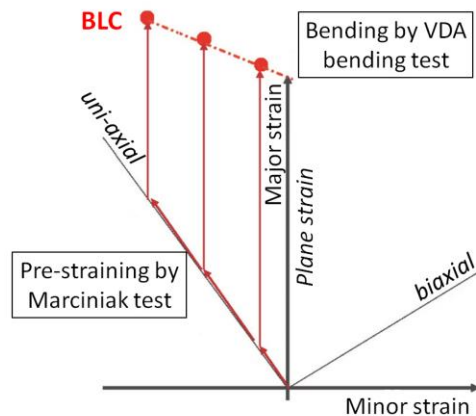


Figure 5. Schematic development of BLC [10].

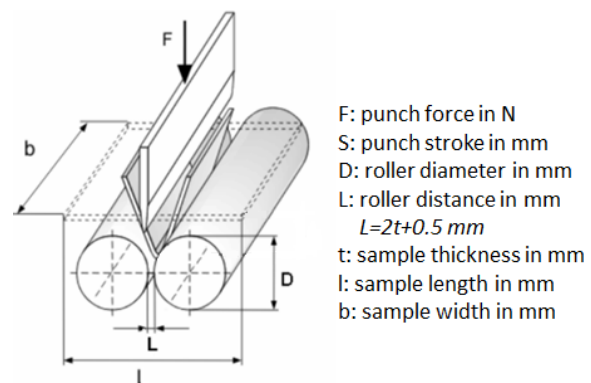


Figure 6. Schematic illustration of the bending device (VDA 238-100).

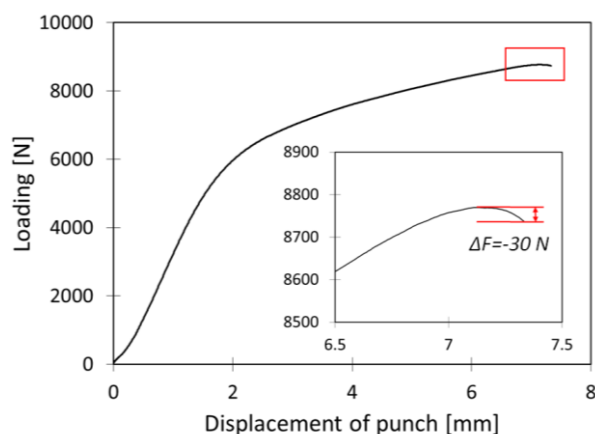


Figure 7. Loading curve in VDA bending test and the defined failure criterion.

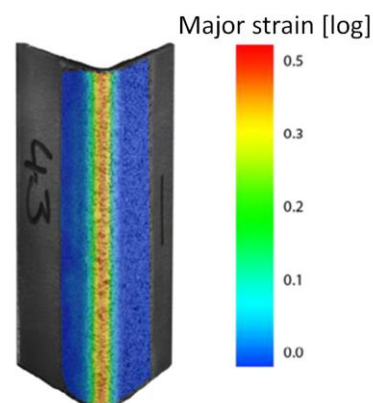


Figure 8. Strain distribution on the surface of the bending samples, measured by optical metrology (GOM ARAMIS) [10].

3. Results and discussion

3.1 Forming Limit Curves (FLC)

As characterized by SEM, the microstructure of DP1180 is not changed by hydrogen charging process. Figure 9 shows the FLCs of the uncharged and pre-charged DP1180 samples measured via the Nakajima test. It is revealed that, the forming limits in different strain states dropped by different amounts. In the uni-axial strain state, no obvious distinction was found; the major strain dropped from 0.11 to 0.10 while the minor strains stayed the same. In the plane strain condition, the forming limit was lower in the pre-charged samples. The major strain decreased from 0.09 to 0.06. However, in the biaxial strain state, a localized necking period was not found in the pre-charged samples. The representative thinning rate diagrams of biaxial samples are shown in Figure 10: in Nakajima tests the uncharged samples first deformed stably and then deformed unstably (Figure 10 (a)). Conversely, in the pre-charged samples instable deformation was not detected, which means the samples underwent stable deformation up until failure (Figure 10 (b)).

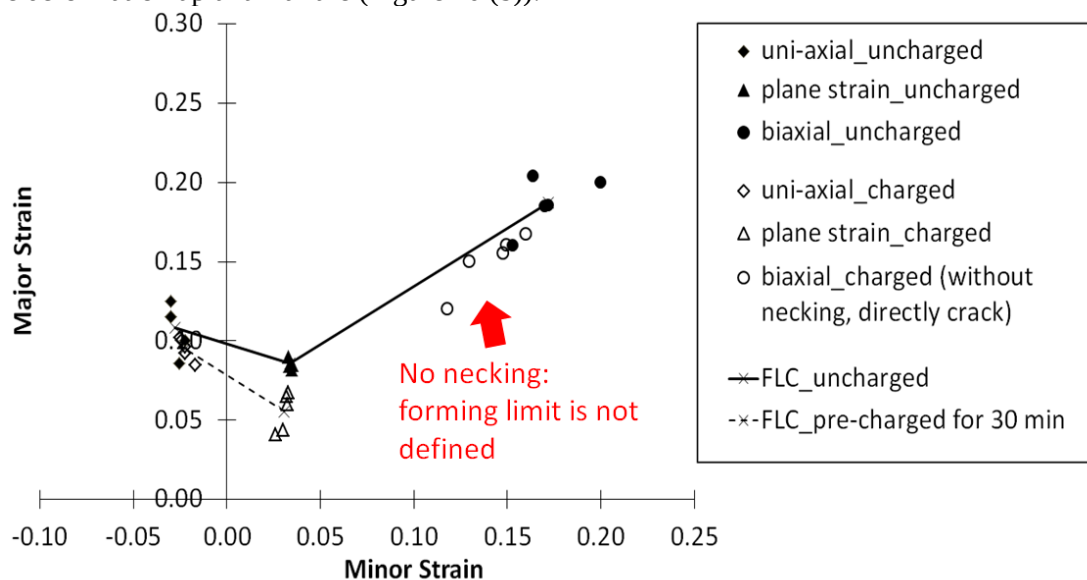


Figure 9. Forming limits of uncharged and charged DP1180 samples in Nakajima tests.

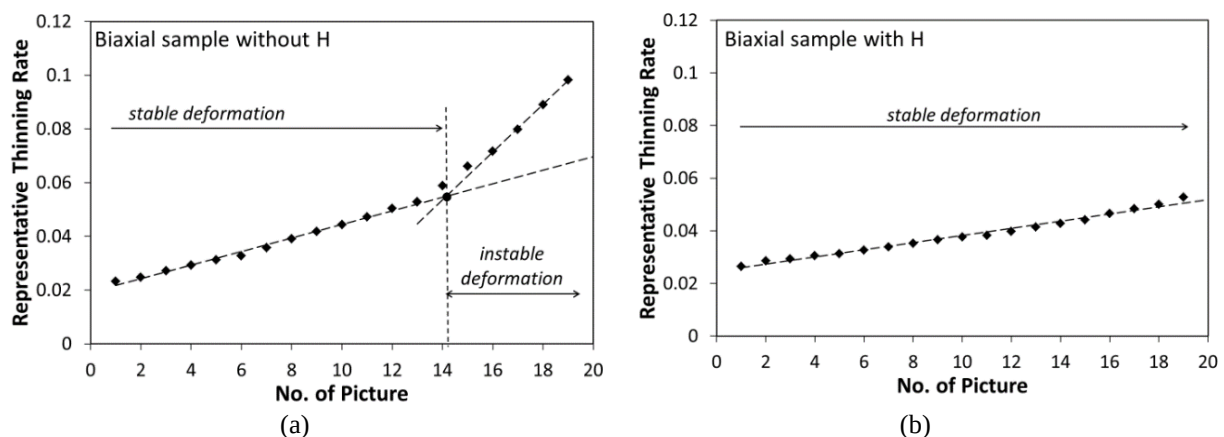


Figure 10. Detection of stable/instable deformation in biaxial condition on (a) uncharged and (b) pre-charged samples of DP1180 in Nakajima tests.

The fracture surfaces of Nakajima samples were analyzed under SEM model, as showed in Figure 11. On the uncharged samples, the fracture surfaces displayed overall ductile fracture with dimples,

indicating plastic deformation. Under stress the dislocations pile up at the potential positions where the cavities are firstly created. The multi-axial stress leads to the growth and merging of the cavities and ductile fractures with dimples to result [14]. The fracture surfaces of the pre-charged sample showed quasi-cleavage fracture in transgranular mode inside the large dimples. After pre-charging a high concentration of hydrogen atoms exist in the trapping sites, and the localized stress gradients act as the driving force for its diffusion. The multi-axial stress activates the hydrogen re-contribution process, therefore the hydrogen atoms concentrate at the top of crack tips, which causes local cleavage fracture. In the biaxial strain state, under both major strain and minor strain, the hydrogen re-concentration is more intense because the expanded lattices provide more space for hydrogen atoms than the compressed lattices. The HELP mechanism explains the formability degradation due to HE in aspect of interaction between hydrogen atoms and dislocations [4, 5]. Local hydrogen enrichment weakens the cohesion force of matrix and causes brittle fractures, as explained in the HEDE mechanism [2, 3].

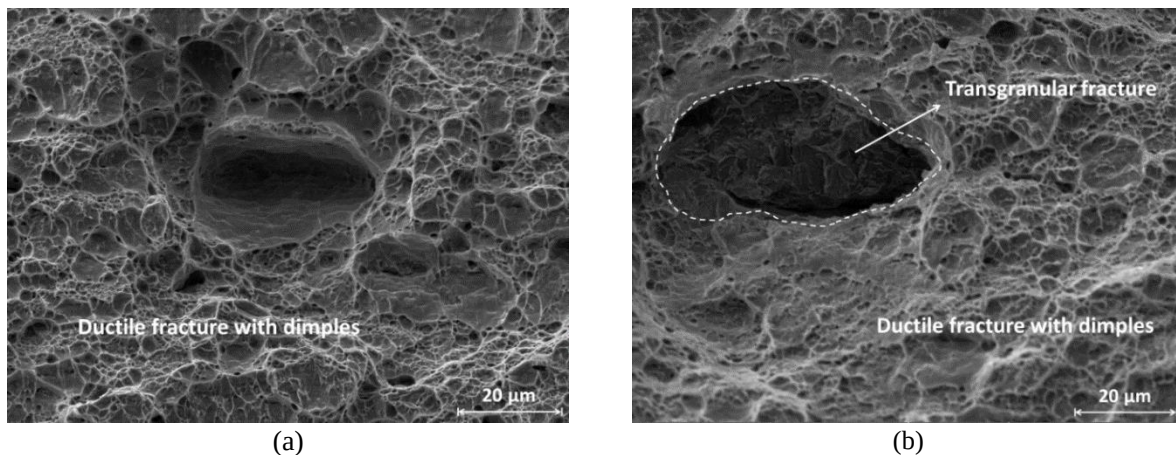


Figure 11. SEM fracture surfaces of (a) uncharged sample and (b) pre-charged sample of DP1180 after Nakajima test, in biaxial strain state.

3.2 Bending Limit Curves (BLC)

Figure 12 shows the failed samples with ca. 2% pre-straining after bending tests. On the uncharged and pre-charged samples, both materials have comparable quality of bending edges. It was demonstrated that the failure mechanism and the bending fracture were identical, independent of hydrogen pre-charging.

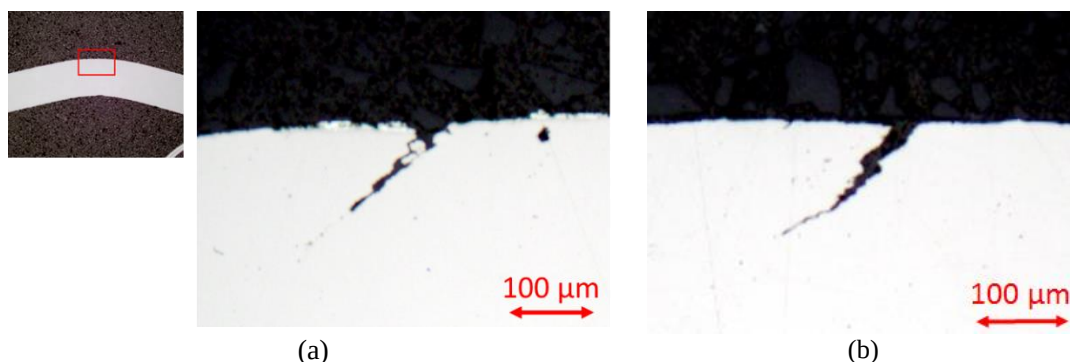


Figure 12. Microscopic images of bending fracture from (a) uncharged and (b) pre-charged DP1180 samples.

The bending limit curve shown in Figure 13 includes uni-axial, plane strain and biaxial pre-loads, is named enhanced Bending Limit Curve (eBLC) [12]. The pre-straining processes under different strain paths provide the distribution of major and minor strains. By the bending process the major strain in

the samples was increased. In Figure 13 it can be seen that after 30 min pre-charging, the critical strains to bending fracture were decreased. This is most likely due to the enrichment of diffusible hydrogen. The comparison of effective strains to bending fracture was illustrated in Figure 14. The degradation of effective strain was defined as an index to evaluate susceptibility to hydrogen, which was calculated according to equation (1):

$$\text{Index (HE)} = \frac{\varphi_v (\text{uncharged}) - \varphi_v (\text{pre-charged})}{\varphi_v (\text{uncharged})} \times 100\% \quad (1)$$

where φ_v is the maximum effective strain without bending fracture. The higher *Index (HE)* stands for higher susceptibility to HE during bending process. For the material without pre-straining, the *Index (HE)* was 31.5%. Therefore, the *index (HE)* of the pre-strained material was higher than that of the material without pre-straining. It is illustrated that after pre-straining, the hydrogen-induced degradation of bendability was higher. Though the hydrogen pre-charging processes of all the samples were same, the samples with pre-straining adsorbed more hydrogen than the samples without pre-straining. Tensile straining played an essential role in providing the trapping sites for hydrogen. Higher hydrogen content led to higher *Index (HE)*.

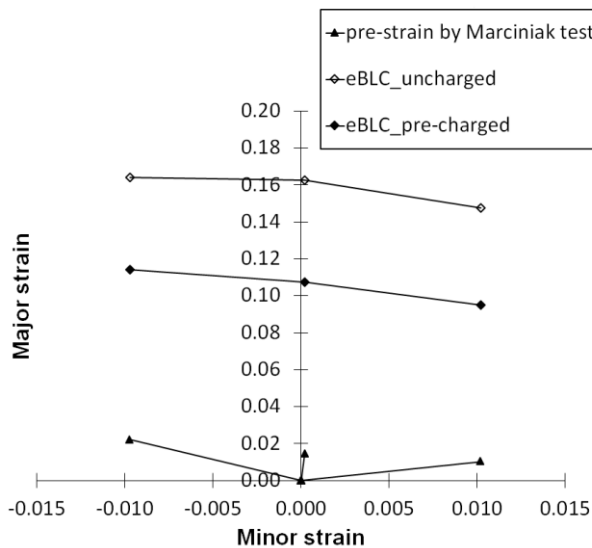


Figure 13. eBLC of uncharged and charged DP1180 samples via VDA-bending tests.

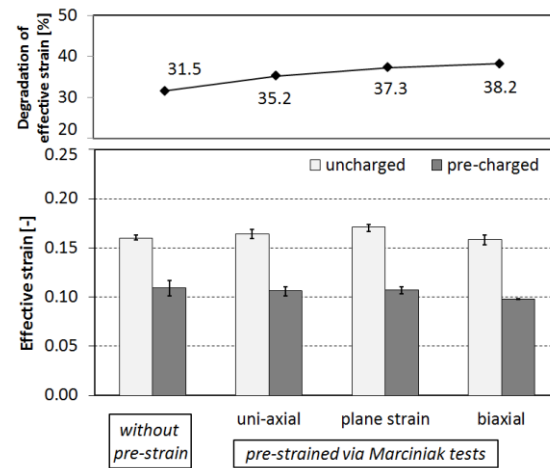


Figure 14. Comparison of effective strains from uncharged and pre-charged bending samples.

4. Conclusion

In the current work, the impact of hydrogen on FLC and BLC in DP1180 steel was investigated via Nakajima tests and 3-point-bending tests with pre-strained samples.

After pre-charging, the forming limits and bending limits were degraded due to the presence of hydrogen. Hydrogen induced degradation of formability is depending on the strain states. In uniaxial strain state, the forming limit is not significantly influenced by hydrogen, while in the plane strain state the forming limit drops to a lower level after pre-charging. The material in biaxial strain state shows the highest susceptibility to HE where the samples fail even before the initiation of necking. The shift of FLC can be explained by HELP and HEDE mechanisms.

Hydrogen plays a critical role when the material is under bending loads. In the study of hydrogen influence on BLC, the bending limits of the as-delivered and pre-strained samples are reduced. The material with pre-straining is more susceptible to HE compared to the material without pre-loads. The pre-strained samples in various strain paths display different in the susceptibility to HE. The susceptibility to HE in different pre-strained material is: biaxial > plane strain > uniaxial > without pre-straining.

In general, FLC and BLC, which are taken as processing criteria for steel sheet materials, are influenced by hydrogen. It means that in actual production processes of car body constructions the impact of hydrogen in AHSS should be considered. The forming and pre-straining processes of hydrogen-existing components should be paid attention to, especially when the strain state is in biaxial strain path. The results of the present work could also be significant for the evaluation of the crash behavior of car body components made of AHSS, in the case of hydrogen presents. In the current work, the punch velocity was set according to the standard. The further work can focus on the hydrogen-induced degradation of formability at different forming speed, to understand the hydrogen diffusion process during the forming process better.

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