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Measurement of edge fracture strain of dual-phase steels by in-plane bending test

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Abstract. Edge ductility of dual phase steels is highly affected by the preparation of the edge and especially shear cutting has a detrimental effect on the formability. In this study, a novel in-plane bending test is used to characterize the edge ductility of dual-phase steels. Digital image correlation technique is employed to calculate the fracture strain along the edge in the desired material orientation. The proposed test setup isolates the material-dependent aspects, namely damage and hardening, from those resulting from testing procedure factors such as contact stresses and friction compared to conventional hole expansion capacity (HEC) test. The results show that the edge crack phenomenon depends on the material orientation.

1. Introduction

Dual-phase (DP) steels provide excellent formability and high strength to weight ratio [1]. They have attracted particular attention due to new environmental initiatives adopted by car industry to reduce the weight and to increase the safety of the car [2]. However, DP steels suffer from the low edge ductility or premature fracture at shear cut edges below the forming limit curves (FLC) [3].

The shear cutting process (such as blanking or punching) severely deforms the edge of material and forms a shear-affected zone (SAZ) at the edge of the material. The fracture surface of the shear cut edge consists of the rollover, burnish, fracture, and burr regions, schematically shown in Figure 1a.

Several tests are available in the literature to assess edge ductility. The hole expansion capacity (HEC) test based on ISO 16630 is the most common test to investigate whether a sheet metal is suitable for forming process or not concerning edge ductility. A schematic of the HEC test can be seen in Figure 1b. It was widely shown that HEC results are sensitive to test parameters such as punch geometry [4], initial hole diameter [5], hole curvature variation [6], edge cutting method [7], direction of strain gradient *i.e.* perpendicular [8] or parallel [9] to edge direction. One reason for this observation can be the complexity of stress state at the edge of the test specimen that is impacted by friction, contact forces, and out of plane deformation. Thus the HEC value could not solely be considered a material characteristic. In other words, the variation in the measured fracture strain [10] significantly impacts engineering interpretation of the results [11]. Furthermore, anisotropy in edge crack sensitivity cannot be captured due to

inherent rotational symmetry in the test. Also, performing digital image correlation (DIC) for local measurement of strain along the edge in an HEC test is not straightforward due to out-of-plane deformation [12]. Alternatively, to remove the contact stress and friction at the edge caused by the conical punch of the HEC test, a hollow cylindrical punch with a flat bottom can be used [13]. This punch geometry produces in-plane deformation without contact and friction between the edge of the hole and the punch [14]. While it seems that a cylindrical punch may provide edge material properties independent of test parameters [15], it also has been reported that fracture can occur far from the edge due to different stress state compared to the the material edge [16]. The material can endure less deformation in the plane-strain condition (lowest point on FLC) than uniaxial stress state. Whereas the hole edge is in a uniaxial stress state, further from the edge it shifts towards a plane strain state, where failure may occur.
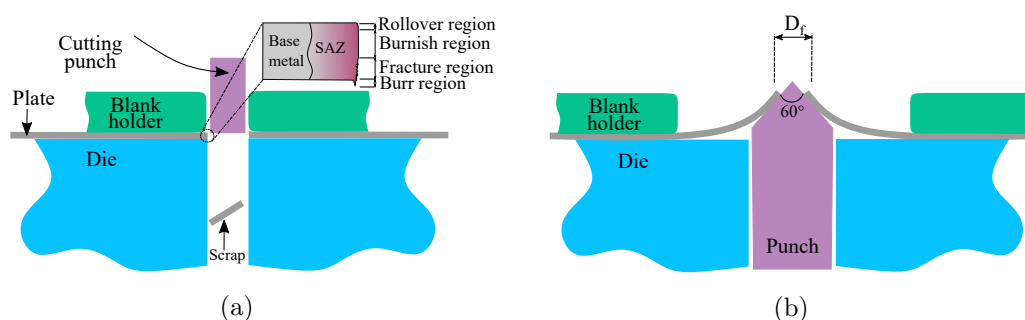

Figure 1: Schematic of a) the punching process and shear affected zone (SAZ) and b) the hole expansion capacity (HEC) test.

Wang *et al.* [17] and Atzema *et al.* [18] introduced the sheared edge tensile test improved (SETi) technique that utilizes a conventional tensile test with sheared edges equipped with DIC for assessing edge ductility. SETi test can be performed in the desired material orientation; However, a tensile test to evaluate edge ductility works only for materials sensitive to edge cracks. Otherwise, failure will occur after necking, which in return makes it challenging to isolate edge ductility. Kobe hole tensile test [19] and side bending test [20] are other alternative tests; independent of the burr orientation, friction, and contact stress. However, the sample geometry used in this study localizes the strain on a tiny portion of the edge, which may not represent the whole sample due to local property variations.

A reliable characterization method for assessing edge ductility of high-strength steel is required to isolate the material-dependent factors such as damage and hardening from structural elements such as contact stresses and friction. It is a prerequisite for understanding the physics of the problem and the root cause of edge cracks. As described earlier, this task is unachievable by current approaches such as the HEC test. In the present research, this challenge is addressed by introducing a novel in-plane bending test to investigate edge ductility. The following sections begin with a comprehensive explanation of the proposed in-plane bending setup, including using digital image correlation in the measurements. Subsequently, two common grades of advanced high-strength steels used in the car industry were selected for the edge ductility investigation by the in-plane bending test.

2. In-plane bending setup
2.1. Fixture design and sample geometry
Recently, an in-plane bending test for sheet metals (Figure 2a) was developed to offer more stability in finding hardening curves at strains above the uniform strain [21]. The strain gradient

that occurs in bending delays the necking, making it ideal for investigating edge ductility. The sample geometry and the location of applied forces for deforming the sample are shown in Figure 2b. The sample design is such that the maximum tension occurs at the top edge of the sample. This provides easy edge preparation by any cutting method for edge ductility study, considering that the upper edge is straight. As it can be seen, there is no friction and no contact stress on the edge at the beam area as opposed to the HEC test.
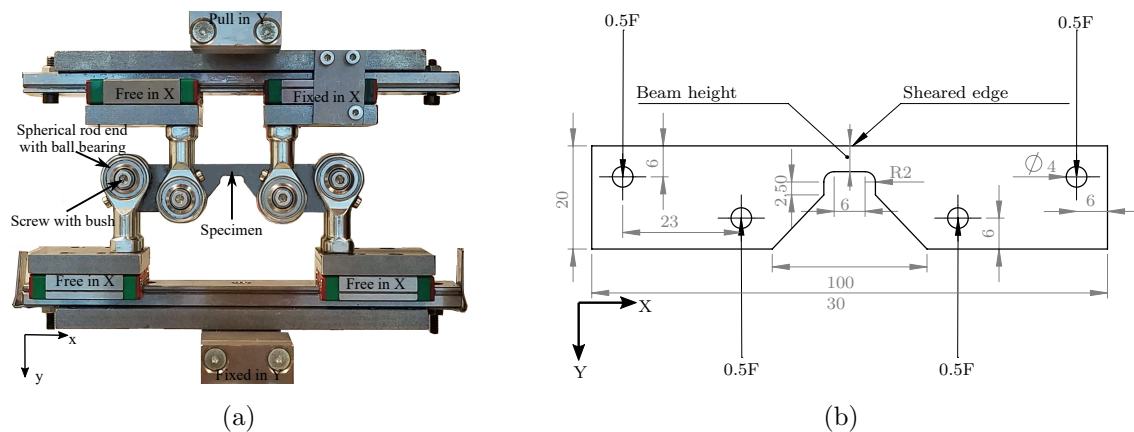

Figure 2: In-plane bending test; a) The test fixture, b) Sample geometry. The dimensions are in millimeter.

2.2. Fracture strain measurement

The fracture strain is required for edge ductility studies, which can be measured by the DIC technique. This technique works based on processing images taken from the beam section of the in-plane bending test during deformation. The method can provide a relatively accurate strain distribution over the edge compared to the HEC value measured by the caliper. DIC commonly uses a white painted background with black speckles on the surface of the sample for creating the best contrast. However, the layer of paint makes crack detection difficult. Thus, a pattern was applied directly on the material surface with the help of spraying the black color without white background. An IDS camera model UI-35910CP-C-HQ revision two equipped with RICOH lens model FL-BC7528-9M was employed for recording a sequence of images. A frame rate of 10 fps with an image resolution of 4912×3684 pixel was chosen. Subsequently, image analysis was done by the open-source DIC code, Ncorr [22]. The subset with a radius of 20 pixels was selected as the DIC parameter. The numerical mean of the strain distribution along the edge is called 'edge strain at fracture'. This value could be used for comparison purposes with the HEC value, considering that the HEC value is also an average quantity over the whole circumference. All reported strains from different tests in the current investigation refer to the logarithmic strain measure.

2.3. Moment-curvature measurement

In order to calculate the moment *vs.* curvature diagram, the applied force (F) was measured by a Zwick tensile machine of 5.0 kN capacity. Then, the moment was calculated by Equation (1).

$$M = \frac{F \cdot d \cdot \cos(\alpha - \beta)}{2} \tag{1}$$

Where d and α, shown in Figure 3, are constant values during rotation, related to the position of the holes on the bending sample, and β is the angle of rotation which was measured by image processing in GOM correlate software. In this method, a local coordinate system was defined with the help of three points located in the rigid part of the sample far from the deformation zone. Subsequently, the rotation (β) during bending was tracked. To calculate the curvature by Equation (2) [23], the angle (θ) between two imaginary lines in the beam area, shown in Figure 3, was followed during bending.

$$\kappa_{\text{beam}} = \frac{\theta}{l_0} \tag{2}$$

where, l_0 is the initial distance between the two lines. The maximum distance between the two lines is 4.5 mm.
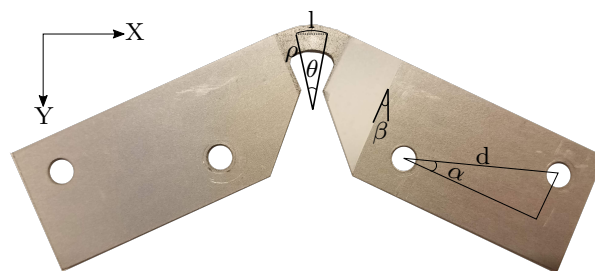

Figure 3: The deformed sample after in-plane bending test.

2.4. Hole expansion capacity test as a reference of the edge fracture strain
Hole expansion capacity tests were done based on ISO 16630. In this test, a hole with a diameter of 10 mm was punched in a rectangular steel plate ($90\,\text{mm} \times 90\,\text{mm}$); subsequently, the hole was expanded by a conical punch until a through-thickness crack was detected. Then, the engineering fracture strain (e_{fracture}) or hole expansion capacity (HEC value) was calculated based on the original and final hole diameter (D_0 and D_f) by using Equation (3). The test was repeated three times.

$$e_{\text{fracture}} = \frac{D_f - D_o}{D_o} \tag{3}$$

3. Design of experiment
Dual-phase steels were used as the test material in this research. A commercial-grade DP800 hot-dip galvanized (EN 10346:2015: HCT780X+Z) and a trial grade aimed at UTS 1000 MPa, taken for early evaluation of edge ductility, referred as DP1000. Both were produced by Tata Steel with a similar thickness of 1.3 mm, as two common grades of advanced high-strength steels in the car industry.

In order to prepare the top edge of samples for edge ductility investigation in the rolling direction (RD) or transverse direction (TD), a shearing tool with adjustable cutting clearance of 2 µm precision was used. A cutting clearance of 12% was chosen, similar to the punching clearance of the hole expansion capacity test. Then, laser cutting was employed for cutting the rest of the edges and holes of the geometry. Also, it was demonstrated by Ref.[24] that the edge fracture strain is influenced by the time between cutting and testing, and it stabilizes after two weeks. Therefore, all tests in this research were performed more than two weeks after cutting the samples to mitigate the time dependency effect. Each experiment was repeated at least five times and at most ten times to ensure the test repeatability.

4. Results

The following sections elaborate on the effect of material orientation on edge ductility by the in-plane bending test. Also, it shows the limitation of the HEC test for measuring the fracture strain in different material orientations.

4.1. The effect of material orientation on fracture strain

The stress-strain curves measured by a tensile test (ISO 6892) in rolling (RD) and transverse (TD) directions of the as-received DP800 material are reported in Figure 4a. The achieved moment-curvature diagrams of the in-plane bending tests based on the methods explained in Section 2.3, are shown in Figure 4b. The overall material anisotropy of DP800 is already observed in the tensile test results, where the uniform elongation in RD is around 2.4 % higher than in TD (Figure 4a). The same trend is observed for edge ductility (Figures 4b), which confirms the dependency of edge ductility to material orientation.
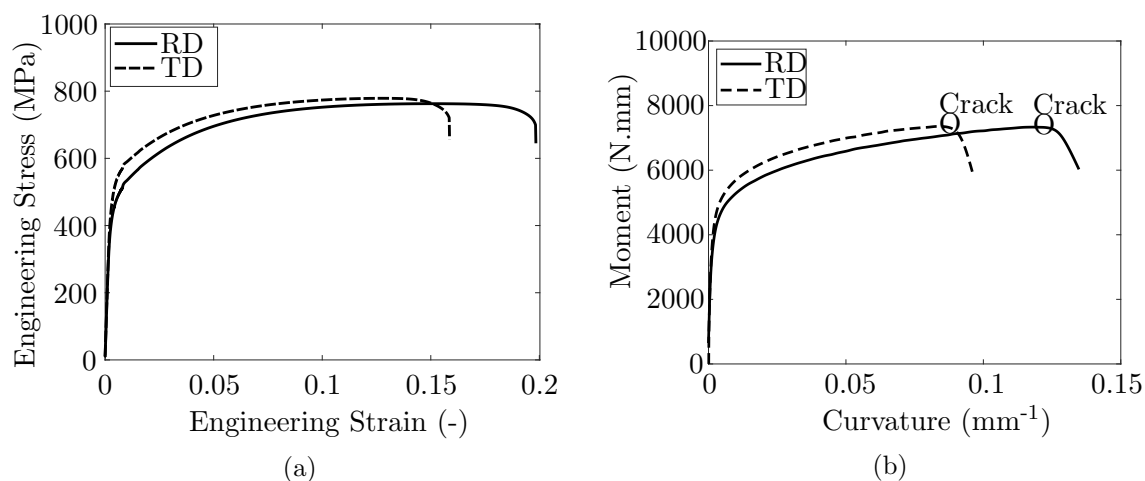

Figure 4: The characterization of DP800 in rolling and transverse directions. a) Stress-strain curve measured by tensile test and b) Moment-curvature diagram measured by bending test.

The strain distribution of the in-plane bending test at at the presence of the edge crack is shown in Figure 5a. It can be seen that the maximum stretch is on the sheared edge of the material. The average strain distribution on the edge is extracted from DIC measurement at the moment of fracture and depicted in Figure 5b, in RD and TD material orientations for DP800 and DP1000. The result shows that the rolling direction performs better with respect to the edge ductility issue for both materials.

The HEC values of DP800 and DP1000 are 0.21±0.005 and 0.22±0.01 respectively; which are close to each other. The direct comparison of the HEC test with the in-plane bending test is not straightforward, considering the complex stress state at edge material during the HEC test due to friction, out-of-plane deformation, and contact stress. The edge crack in HEC test occurred in the rolling direction as indicated in Figure 5c, where the major principal stress direction is parallel to TD. This implies that the transverse direction is the weakest material orientation for edge cracks. This shows that it is not possible to measure edge ductility of the material in the rolling direction with the HEC test due to inherent rotational symmetry in the test, which means that the weakest direction determines the result.
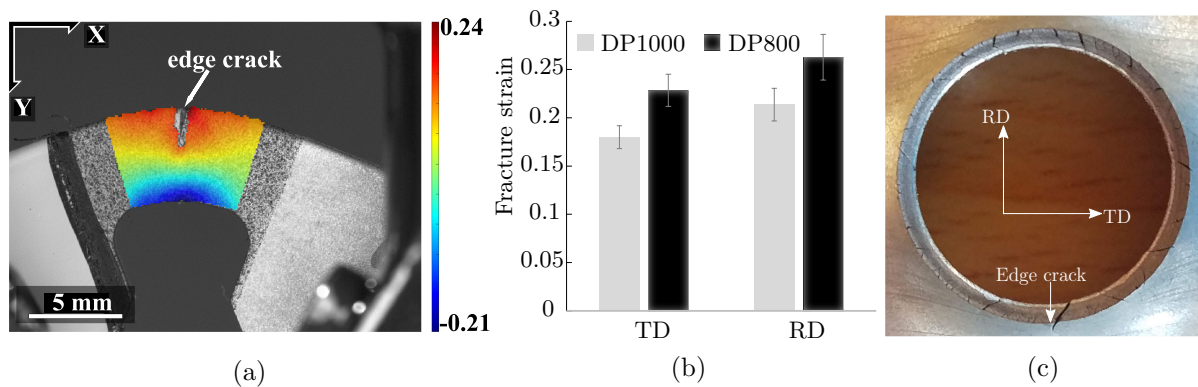
Figure 5: a) The edge strain distribution after fracture of in-plane bending test of DP800 material. b) The fracture strain in transverse and rolling directions of DP800 and DP1000. C) Hole expansion capacity test of DP800. The major vertical cracks confirm that the weakest direction is TD.

4.2. The edge crack initiation and growth

The edge of the material after the bending test with vertical and horizontal cracks is shown in Figure 6a. The horizontal crack in region 'A' was created due to shear cutting and not the bending test. Interestingly, it does not play a role in the initiation of the edge crack during bending. Figure 6b and 6c show that multiple vertical cracks initiated in the burr region, and there are a few other cracks that encompass the whole thickness. These micro-cracks are not present in the rollover region. It is in agreement with the higher HEC value reported by [16] for cases with the burr in direct contact with the punch of the HEC test than the specimen with the burr away from the punch. Actually, the punch contact in the HEC test delays the crack initiation at the side of contact by applying compressive stresses. Also, the out-of-plane deformation imposes more deformation at the side of the plate away from the punch. In other words, the material does not necessarily fail at the weakest location and the result of HEC test can be influenced by contact stress, punch type and friction [4, 14]. This is not the case for the in-plane bending test, and hence, the in-plane bending test gives a better representation of pure material behavior.
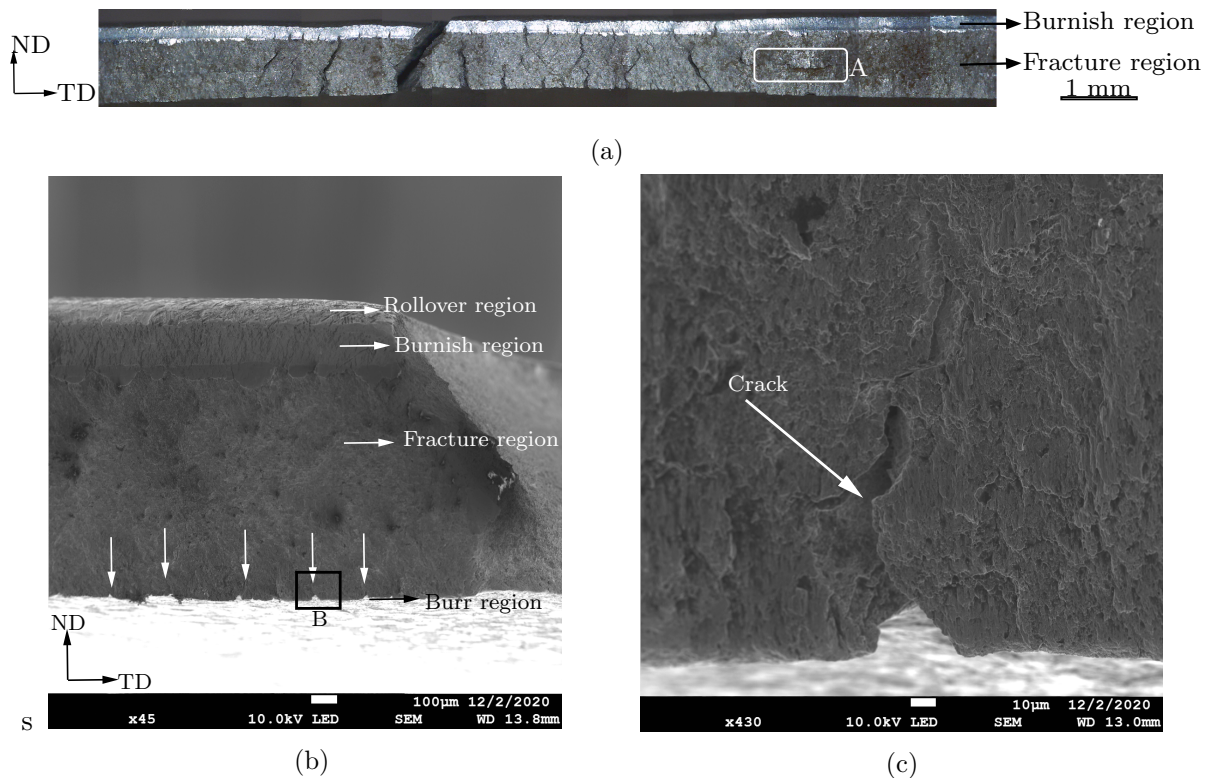
(a)

(b)

(c)

Figure 6: The edge appearance after bending test. a) Multiple vertical cracks are visible. Region A shows a horizontal crack created by shear cutting process. b) The microcracks initiated at burr region, while there is no visible micro crack at the roll over region. c) higher magnification of rectangle B.

5. Conclusions

In this study, an in-plane bending test was employed as a novel method for assessing edge ductility of two common steel grades in the automobile industry. The investigation proved that the edge crack phenomenon depends on material orientation. A sheared edge parallel to the transverse direction has a lower fracture strain. Therefore, the in-plane bending test is reliable for measuring edge ductility, considering that it provides more details of fracture strain than the HEC test in the desired material orientation. Also, the edge properties along the thickness direction are inhomogeneous; many micro-cracks have been observed on the burr side while only a few spread the entire thickness.

6. Acknowledgment

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