Solid State Phenomena
ISSN: 1662-9779, Vol. 388, pp 91-100
doi:10.4028/p-UDAN9u

Submitted: 2026-01-16
Revised: 2026-02-16
Accepted: 2026-02-18
Online: 2026-04-15

Asymmetric Hole Expansion Test (aHET) for Direct Measurement of Orientation-Dependent Tensile Fracture Strain

Raphaël Pérot[1,a*], Vincent Grolleau[1,2,b] and Dirk Mohr[1,c]

[1]Chair of Artificial Intelligence in Mechanics and Manufacturing, Department of Mechanical and Process Engineering, ETHZ Zurich, Switzerland

[2]Univ. Bretagne Sud, FRE CNRS 6027, IRDL, F-56100 Lorient, France

[a*]rperot@ethz.ch, [b]vincent.grolleau@univ-ubs.fr, [c]dmohr@ethz.ch

Keywords: hole expansion test, asymmetric hole expansion test, edge fracture, sheet anisotropy, fracture initiation criterion.

Abstract. The flangeability of sheared edges in sheet metal forming is commonly evaluated using the ISO 16630 Hole Expansion Test (HET), in which fracture initiates at the edge under predominantly uniaxial tensile loading. For high-quality edges, this test can be interpreted as providing the strain to fracture under proportional uniaxial tension; however, the measured fracture strain is restricted to a single material-dependent sheet orientation. In this work, a novel experimental approach is proposed to directly measure the uniaxial tensile fracture strain in a predefined sheet orientation using digital image correlation (DIC). The method, termed the Asymmetric Hole Expansion Test (aHET), is derived from the standard HET through the introduction of a novel asymmetric punch geometry. This modification promotes accelerated edge stretching along a controlled direction, enabling orientation-specific characterization of fracture strain. The capability of the aHET to characterize direction-dependent strains to fracture under uniaxial tension is demonstrated on a DP450 dual-phase steel. The consistent fracture initiation at the edge along the predefined fracture direction, combined with the low scatter of the measured fracture strains across repeated tests for all three investigated sheet orientations, demonstrates that the aHET is well suited for identifying the strain to fracture under proportional uniaxial tensile loading for the calibration of fracture initiation models.

Introduction

The edge flangeability of sheet metals is most commonly assessed using the Hole Expansion Test (HET), standardized in ISO 16630 [1]. In this procedure, a circular hole is first produced by shear cutting, after which a conical punch is driven through the hole until fracture occurs at the edge (Fig. 1 a, b). For materials exhibiting limited plastic anisotropy, the hole expansion remains approximately uniform during deformation. Under these conditions, the hole diameter measured at fracture provides a reliable indicator of sheared-edge stretchability.

Besides, during the HET, the circular edge located on the specimen surface opposite the punch undergoes proportional uniaxial tensile loading until fracture, with the principal strain direction locally tangential to the hole edge. Provided that the edge quality is sufficiently high, the test is therefore attractive for calibrating fracture initiation models under uniaxial tensile stress state, such as the Hosford-Coulomb model [2]. The latter is usually calibrated under uniaxial tension using the central hole tensile test which has the downside of requiring inverse finite element analysis after performing the test to identify the strain to fracture, since the critical area lies in the mid-thickness plane of the specimen [3].

However, due to the axisymmetric nature of the HET, the position along the edge where fracture initiates is unpredictable and may occur in sheet orientations that do not correspond to the standard rolling, transverse, or diagonal directions [4,5]. Consequently, the application of Digital Image Correlation (DIC) on the top surface of the specimen is inconclusive, since the hole edge undergoes significant rotation and translation in the punch direction [6]. The use of three-dimensional DIC (3D-DIC) with tilted camera configurations targeting a specific edge location is likewise impractical. Even for materials exhibiting pronounced plastic anisotropy creating local strain maxima along the edge, fracture initiation still follows preferred material directions, resulting in competing potential sites for crack initiation [7-9]. As an alternative, flat-headed punches have been investigated for hole expansion, as they facilitate the application of DIC. However, flat hole expansion tests were shown to be unsuitable for identifying the uniaxial tensile strain to fracture, since fracture initiates away from the hole edge, in a transition region toward plane-strain tension [10,11].

Although the conical hole expansion test is not well suited for direct DIC measurements, it remains attractive for the characterization of the uniaxial tensile strain to fracture. To circumvent the limitations associated with DIC, Pathak et al. proposed estimating the equivalent fracture strain solely from the hole diameter at fracture, averaged over the hole circumference [12]. However, this approach neglects the influence of plastic anisotropy and was therefore shown to have limited applicability [13]. To address this shortcoming, Narayanan et al. introduced an alternative estimation method that incorporates plastic anisotropy by evaluating the local outer-edge hole expansion ratio in the direction of the first crack at fracture initiation. For a CP800 steel exhibiting pronounced anisotropy, this method showed improved agreement with anisotropic simulations compared to the approach of Pathak et al. [13]. Despite these encouraging results, the uniaxial tensile fracture strain can still be identified in only one direction, namely the direction in which the first crack appears. This direction may either vary randomly or remain unchanged across repeated tests, depending on the material's anisotropy. Consequently, the conventional conical hole expansion test does not allow assessment of potential anisotropy in the fracture locus.

In view of both the advantages and the limitations of the Hole Expansion Test for the characterization of uniaxial tensile fracture strain, a novel experimental method is proposed: the Asymmetric Hole Expansion Test (aHET). The aHET may be regarded as a modification of the conventional conical HET, in which an asymmetrically shaped punch is used to promote accelerated stretching of the hole edge in a predefined direction. This controlled localization of deformation enables local strain measurements by 3D-DIC and allows assessment of fracture anisotropy, in contrast to the standard HET.

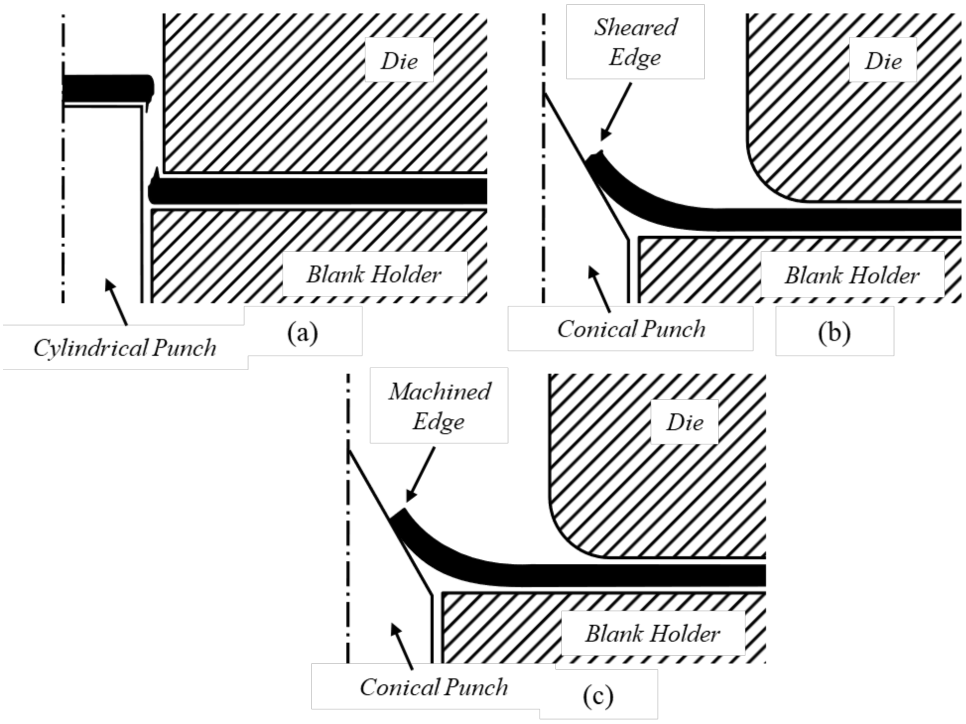


Fig. 1. Axisymmetric views of (a) hole shear cutting and (b) conical punch hole expansion as described by norm ISO 16630 for sheared edge flangeability characterization [1]. Axisymmetric view of (c) conical punch hole expansion for uniaxial tensile fracture strain characterization as described by Pathak et al. [12].

Experiment

Asymmetric Hole Expansion Test (aHET).

In the Hole Expansion Test (HET) with a machined edge inspired by the norm ISO 16630 and described by Pathak et al. (Fig. 1 c), the use of DIC on the top of the specimen is impractical since the hole edge moves vertically but not at the same pace as the punch because of friction and clamping [12]. To overcome this limitation of the machined edge HET, we propose to replace the conical punch in this test with an asymmetric punch to have a predefined direction of failure. Cameras directed at the critical area can then be installed a priori to perform 3D-DIC.

More precisely, the punch design consists of a half-elliptical (with a ½ ellipse radii ratio) and half-circular top face which is homothetically projected into a conical-like shape. The projection along the circle center results in a larger punch angle at the ellipse apex than on the circular-side (Fig. 2). As a result, the hole edge is preferentially stretched in this fixed direction throughout the test, leading to a consistent and repeatable fracture initiation location.

Similarly to the machined edge HET (Fig. 1 c), the asymmetric punch is forced into the clamped specimen up to fracture in the critical area, with a speed of 2 mm/min. No lubricant was applied between the punch and the specimen, given the negligible influence of lubrication in the conventional HET demonstrated by Larour et al. [11].

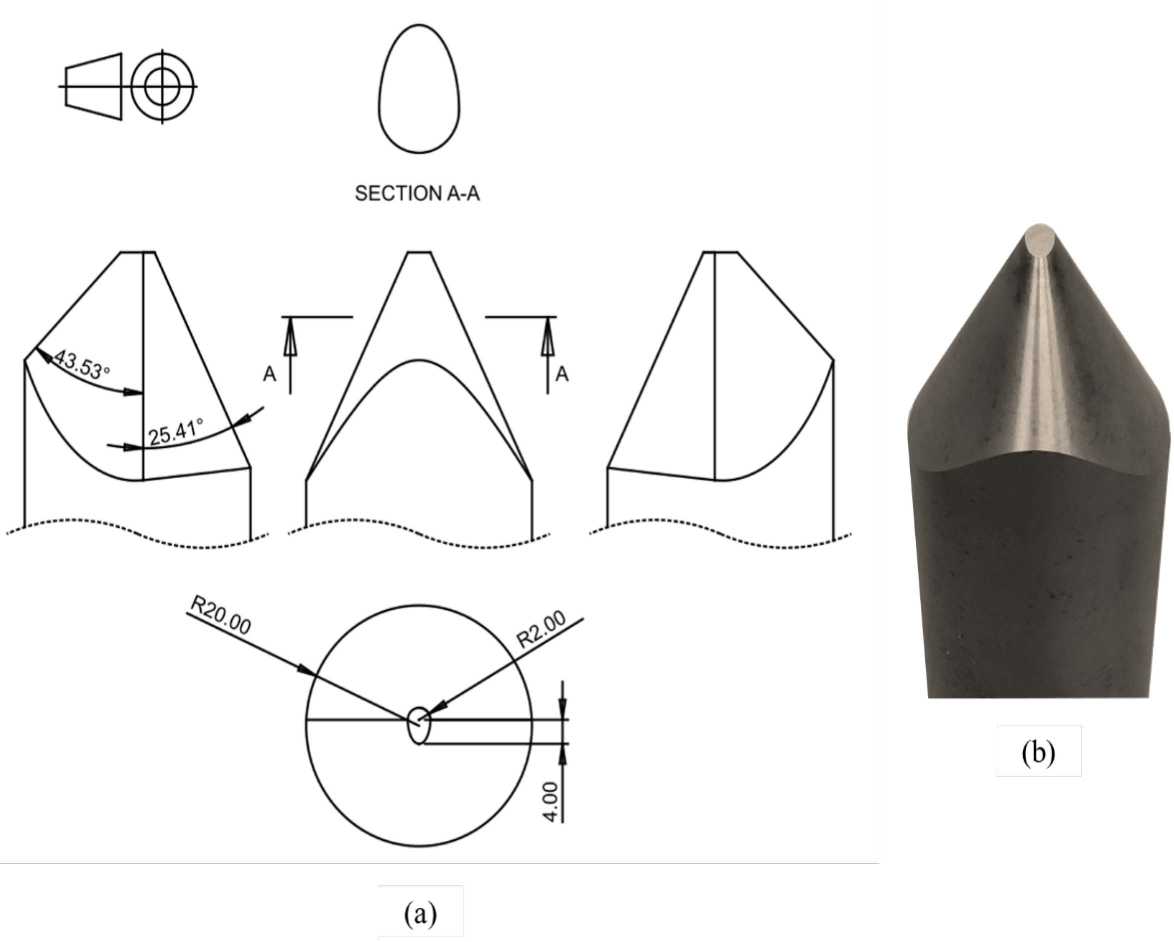


Fig. 2. (a) Technical drawing and (b) front view of the proposed Asymmetric Hole Expansion punch.

Besides, a larger hole diameter reduces the stress gradient in the critical region, thereby improving the accuracy of strain-to-fracture measurements obtained by 3D-DIC. However, increasing the hole size also leads to a larger relative displacement at failure between the specimen and the punch, which may cause the critical region to move out of the field of view of the cameras. Conversely, reducing the hole diameter increases the stress gradients in the critical area, while the speckle pattern becomes relatively coarse with respect to the region of interest and degrades DIC measurement accuracy. To balance these opposing effects, the hole diameter was reduced from the conventional 10 mm specified in norm ISO 16630 to 7 mm.

Furthermore, in the conventional ISO 16630 HET, the circular hole in the center of the specimen is obtained by shear cutting through a punching operation that precedes the hole expansion step (Fig. 1 a) [1]. The obtained edge therefore presents a shear affected zone which substantially affects the stretchability of the material during hole expansion (Fig. 1 b) compared to machined edges obtained through waterjet cutting or milling [14]. Roth and Mohr studied the effect of the machining technique on the size of the machining affected zone when introducing a 5 mm hole in a 1 mm thick sheet of DP780 steel. They concluded that using drilling and reaming sequentially could reduce the depth of the pre-damaged zone to only 5 µm [3]. Moreover, in the methodologies from Pathak et al. and Narayanan et al. using conventional HET to characterize uniaxial tensile fracture strain, the hole in the center of the specimen was machined by sequentially drilling and reaming instead of the conventional shear cutting step from ISO 16630 [12,13]. The resulting edge condition was considered sufficient for the base material to be calibrated using such specimens. Besides, simulations of the hole expansion test with a perfect edge were conducted and showed results in accordance with the experimental results obtained with a drilled and reamed hole, suggesting that this machining procedure results in a negligible edge pre-damage [13]. Pathak et al. similarly concluded that drilling and reaming could be considered as ideal machining conditions and obtained substantial increase in hole expansion compared to sheared edge conditions [15]. Dykeman et al. finally showed that the apparent edge damage induced by waterjet cutting on a grade of advanced high strength steel was less than 5 µm deep [16].

Taking these considerations into account, the hole in the center of the specimen was first machined to a hole diameter of 6.8 mm with high precision waterjet cutting of Q5 quality. Then, the hole was reamed and increased to a 7 mm hole diameter, to attain the desired reaming edge quality. After reaming, the hole exhibits machining patterns from the reamer over the whole thickness of the specimen, indicating a consistent hole radius along the thickness direction.

Experimental Setup.

A circular specimen with a diameter of 130 mm is clamped with four M10 screws between a die (2) and a blank holder (3) with inner hole diameters of 80 mm. The specimens (1) are pierced in their center first with waterjet cutting 0.1 mm in radius below the target hole radius and then reamed to attain the desired 7 mm hole diameter (Fig. 3 a). The specimen orientation is set using notches in its circumference, which fit into the clamping screws. The die set is rigidly connected to the upper crosshead of a universal testing machine. The punch (5) is fixed within a punch holder (6) and placed on self-aligning platens attached to the lower crosshead of the machine. The punch holder is connected to the die set through an alignment system (7) consisting of three beams. Its purpose is to prevent the punch from rotating, while allowing for in-plane displacement. Consequently, the direction of highest stretching remains unchanged through the test while the transverse load transmitted to the machine is negligible. Note that the tensile load in hole expansion is applied tangentially to the edge, so the tested direction is parallel to ellipse's smaller diameter (Fig. 2 a).

Two cameras (8) are positioned to monitor the critical region of the specimen, specifically the hole edge near the apex of the punch ellipse (Fig. 3 b). They are tilted and focused on a circular area approximately 5 mm in diameter at the start of the test. Due to the combined rotation and vertical displacement of the edge during deformation, changes in the camera-to-edge distance remain negligible, ensuring high spatial resolution of approximately 10 µm/pixel throughout the test up to fracture. 3D-DIC is then performed using the camera recordings with the VIC-3D software.

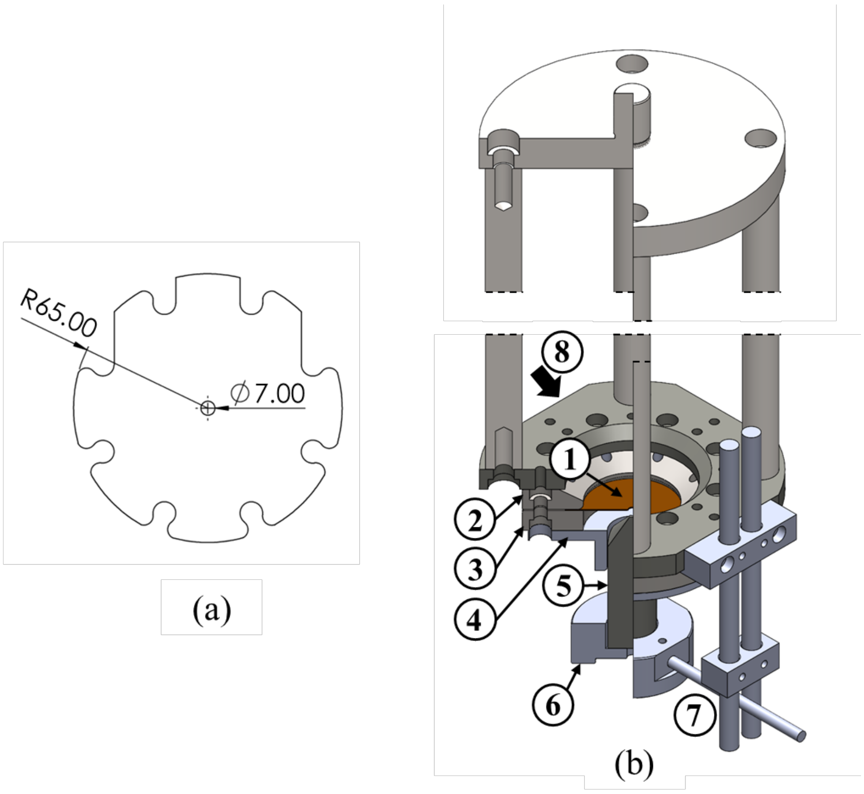


Fig. 3. (a) Specimen, and (b) experimental setup of the Asymmetric Hole Expansion Test: (1) specimen, (2) die, (3) blank holder, (4) punch guide, (5) asymmetric hole expansion punch, (6) punch holder, (7) auto-alignment system, and (8) direction of the cameras.

Material.

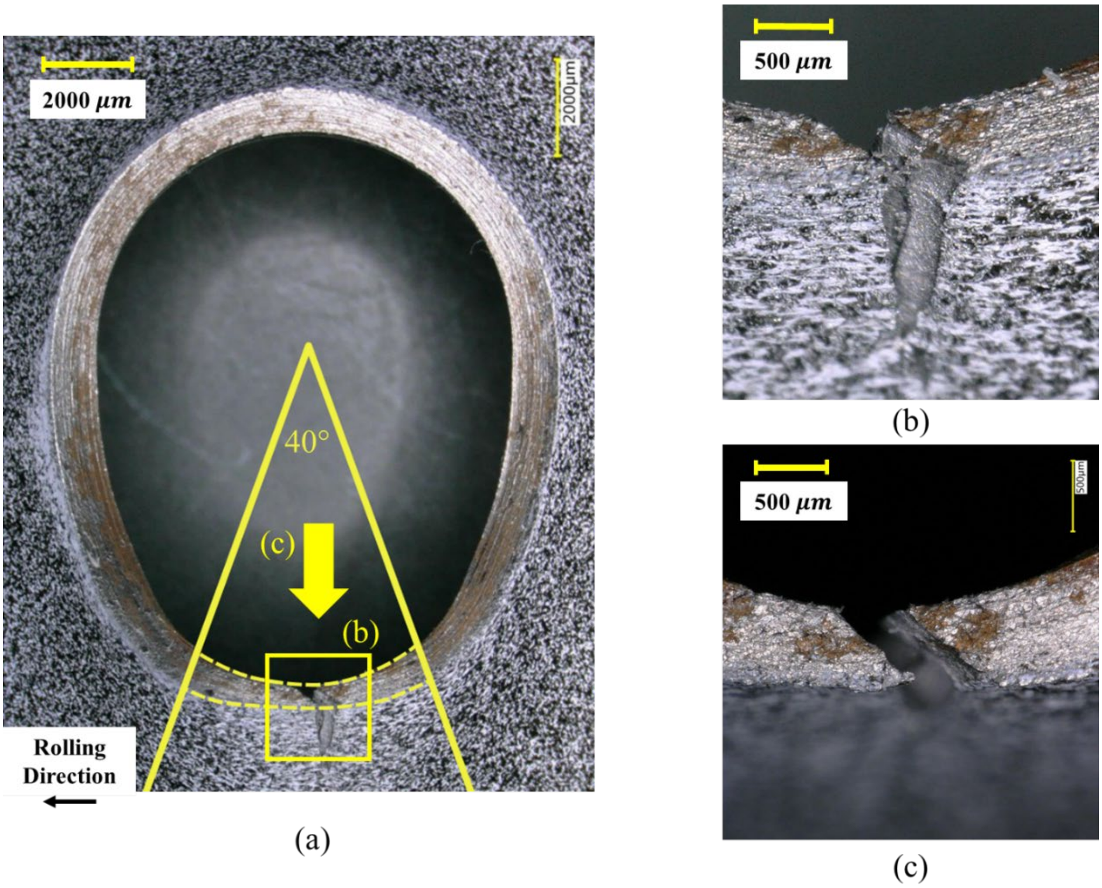
Tests are conducted for a 1.60 mm thick DP450 dual-phase steel exhibiting significant plastic anisotropy, in three sheet orientations (0°: rolling direction, 45°: diagonal direction, and 90°: transverse direction), and with three repeats per orientation. The yield strengths and Lankford ratios of the material under those three orientations are given in Table 1.

Table 1. Direction-dependent yield strengths and Lankford ratios of the studied DP450. 0° denotes the rolling direction.

Orientation	Yield strength [MPa]	Lankford ratio [-]
0°	532	0.96
45°	544	0.79
90°	540	1.17

Results

In every test performed, the fracture systematically initiated at the expected location, i.e. at the apex of the ellipse, and on the edge on the surface opposite the punch (Fig. 4 a). In each case, the crack appeared perpendicular to the edge on the surface of the specimen (Fig. 4 b) but propagated through the surface in a slant manner (Fig. 4 c). A significant thickness reduction can be observed in the critical area. It is moreover interesting to note that this strain localization is highly confined spatially, with a post-mortem thickness already approximately twice as large 20° away from the crack (Fig. 4 a).



(a)

(b)

(c)

Fig. 4. Specimen after the test for the first repeat with fracture initiation under uniaxial tension in the rolling direction: (a) top view, (b) close-up view in the fracture initiation area and (c) tilted close-up view. In (a), a 40° cone delimits the necking area, and the two edges of the hole are highlighted in this region with dotted lines.

This small size of the localization area is also captured by the DIC-derived strain field on the surface of the specimen. Indeed, the effective strain drops to 0 within a few millimeters from the critical area (Fig. 5). One should also notice that the resolution remains good enough through the test for DIC to track the area of interest up to fracture despite the important ductility of the material.

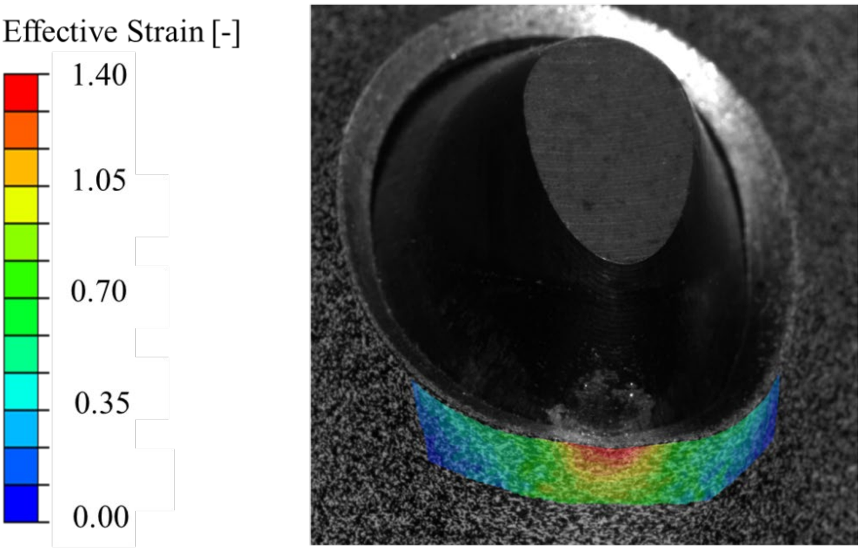


Fig. 5. Effective strain field derived from the DIC-computed strain fields in the critical area, overlaid on the view of one of the cameras at the onset of fracture for the first repeat of the test under the rolling direction.

Since the DIC cannot provide the strain field at the edge, the edge fracture strain was obtained by linear extrapolation of the effective strain field up to the edge. The obtained uniaxial tensile strains to fracture, as well as the standard deviation and average value per tested sheet orientation, are given in Table 2.

Table 2. Uniaxial tensile fracture strains obtained by performing Asymmetric Hole Expansion Tests.

Orientation	Repeat	Von Mises Effective Strain at the edge at the onset of fracture [-]
0°	1	1.36
	2	1.36
	3	1.38
	Mean±SD	**1.36±0.01**
45°	1	1.25
	2	1.26
	Mean±SD	**1.26±0.01**
90°	1	1.36
	2	1.30
	3	1.28
	Mean±SD	**1.31±0.03**

Additionally, we provide a scatter plot of all the strains to fracture obtained from the tests, organized by sheet orientations (Fig. 6).

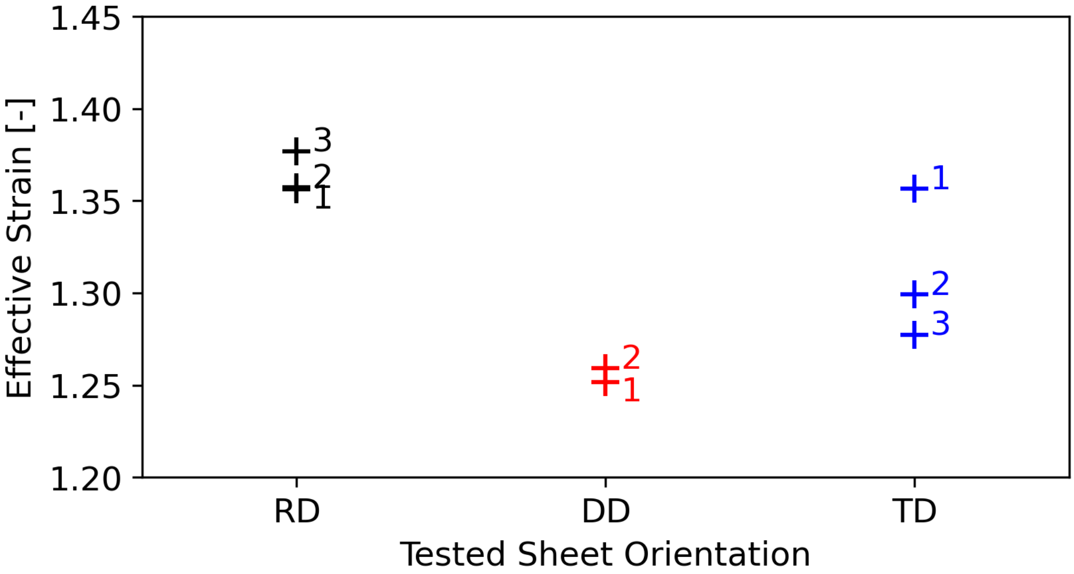
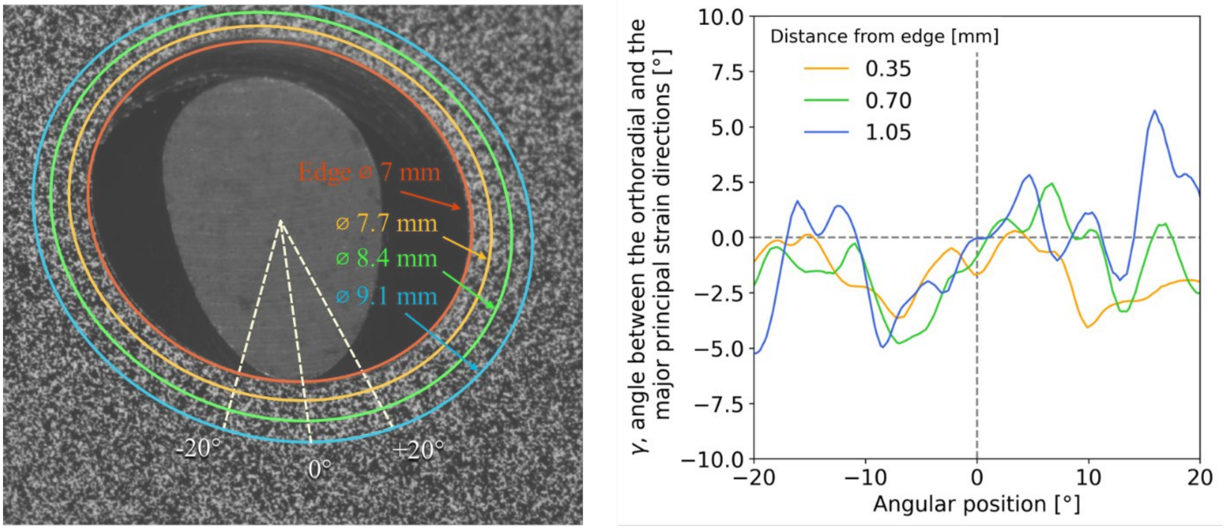


Fig. 6. Distribution of the uniaxial tensile strains to fracture identified directly using the Asymmetric Hole Expansion Test for the studied DP450 under different sheet orientations (with RD, DD and TD respectively for rolling, diagonal and transverse direction). The repeat number is indicated next to each point.

Finally, to ensure that the asymmetry of the proposed test does not alter the uniaxial tensile loading observed at the hole edge in conventional HET, we provide in Fig. 7 the angular distributions obtained from DIC of the angle γ between the orthoradial direction, defined as locally tangential to the hole perimeter, and the local major principal strain eigen-direction.



(a) (b)

Fig. 7. First repeat of the test with uniaxial tensile loading under the rolling direction: (a) specimen at the beginning of the test in the DIC reference configuration with white dotted lines delimiting the critical area (0° corresponds to the location of fracture initiation); and (b) distribution of the major principal strain direction with respect to the orthoradial direction at different distances from the edge in the critical region at the onset of fracture.

Discussion

Firstly, we note that the goal to attain consistent crack location with this test is achieved. We observed a systematic crack initiation at the apex of the ellipse (Fig. 4). Moreover, the fracture observed is comparable to the one obtained with conventional HET [14]. This property could then be used to assess the fracture anisotropy of the material under uniaxial tensile loading. Indeed, the measured average uniaxial tensile strains to fracture differ from up to 0.10 depending on the sheet orientation with 1.36, 1.26 and 1.31 for the rolling, diagonal and transverse directions respectively (Table 2). This fracture anisotropy seems moreover to hold over repeats with a diagonal strain to fracture systematically below the one measured in the rolling and transverse directions (Fig. 6).

Besides, the resolution of the cameras throughout the test proved to be sufficient for DIC, yielding the strain field up within a few dozen micrometers from the edge (Fig. 5). Therefore, the uncertainty introduced by the linear extrapolation is limited since the distance on which strain extrapolation is performed is also limited. This seems to be confirmed by the effective strains to fracture obtained, which exhibit a very limited scatter within a given sheet orientation with standard deviations ranging from 0.01 to 0.03 (Table 2).

Regarding the stress state in the fracture initiation area, the visible hole edge at which the fracture strain is measured is subjected exclusively to stresses in the orthoradial direction. The material thus necessarily undergoes uniaxial tensile loading stress state, analogous to that encountered in conventional HET. Moreover, the angle γ remains relatively constant at 0.35 mm from the edge and up to 20° away from the fracture location with values ranging from -4.1° to 0.3°. Even further away, the variations of γ in the critical area at 0.70 mm and 1.05 mm from the edge remain limited, ranging from -4.8° to 2.4° and from -5.2° to 5.7° respectively. This indicates that the major principal strain is constantly orthoradial in the critical area, and in a comfortably large area around the fracture initiation location.

Conclusion

In this paper, a novel experimental method is introduced to identify the direction-dependent strain to fracture of sheet metal material under uniaxial tensile loading. The proposed Asymmetric Hole Expansion Test (aHET) consists of a direct method where the fracture initiation location is predefined by the experimental set-up, and the strain to fracture can then be measured through 3D-DIC using cameras taking high resolution images of the critical area.

Demonstration experiments showed consistent fracture initiation locations over multiple repeats on specimens extracted from a DP450 dual-phase steel. The fracture initiates at the specimen's upper edge which undergoes proportional uniaxial tensile loading throughout the test. Furthermore, the repeatability of the test in terms of measured strain to fracture is high for each of the tested sheet orientations. The fracture anisotropy of the material under uniaxial tensile loading could be characterized. Overall, the aHET appears to be a good candidate for replacing other more complex experiments used for fracture model calibration under uniaxial tension, such as the central hole tensile test which requires inverse finite element analysis.

The experimental setup needed to perform the aHET is very accessible. Starting with a standard hole expansion device, one only needs to replace the punch and place two cameras pointing at the fracture initiation area. In this work, the device used was designed to be mounted in a universal testing machine, preventing the transmission of any transverse loads. The simplicity of this aHET setup also makes it a promising candidate for high-throughput testing.

References

[1] Metallic materials - Sheet and strip - Hole expanding test, 16630, International Organization for Standardization, p 1-7. (2017).

[2] Mohr, D., & Marcadet, S. J., Micromechanically-motivated phenomenological Hosford-Coulomb model for predicting ductile fracture initiation at low stress triaxialities. International Journal of Solids and Structures, 67–68, 40–55. (2015).

[3] Roth, C., & Mohr, D., Ductile fracture experiments with locally proportional loading histories. International Journal of Plasticity. (2016).

[4] Paul, S. K., A critical review on hole expansion ratio. Materialia, 9. (2020).

[5] Barnwal, V. K., Lee, S. Y., Yoon, S. Y., Kim, J. H., & Barlat, F., Fracture characteristics of advanced high strength steels during hole expansion test. International Journal of Fracture, 224(2), 217–233. (2020).

[6] Barlo, A., Sigvant, M., Pérez, L., Islam, M. S., & Pilthammar, J., A Study of the Boundary Conditions in the ISO-16630 Hole Expansion Test. IOP Conference Series: Materials Science and Engineering, 1238(1), 012031. (2022).

[7] Li, Z., Chang, Y., Liu, W., & Lian, J., Predicting edge fracture in dual-phase steels: Significance of anisotropy-induced localization. International Journal of Mechanical Sciences, 274. (2024).

[8] Plosila, P., Kesti, V., Hannula, J., Kömi, J., & Kaijalainen, A., A comparison between tensile and hole expansion properties in 800 MPa tensile strength grade hot-rolled steels. Materials Today Communications, 40. (2024).

[9] Park, H. S., Barlat, F., & Lee, S. Y., Comparison of anisotropic yield functions and calibrations for accurate thickness prediction in hole expansion test. Journal of Materials Processing Technology, 319. (2023).

[10] Abedini, A., Narayanan, A., & Butcher, C., On the flat punch hole expansion test of sheet metals: Mechanics of deformation and evaluation of anisotropic plasticity models. Mechanics of Materials, 191. (2024).

[11] Larour, P., Freudenthaler, J., Grünsteidl, A., & Wang, K., Evaluation of Alternative Stretch Flangeability Testing Methods to Iso 16630 Standard. Conference Proceedings - Innovations for the sheet metal industry, 188. (2014).

[12] Pathak, N., Butcher, C., Worswick, M. J., Bellhouse, E., & Gao, J., Damage evolution in complex-phase and dual-phase steels during edge stretching. Materials, 10(4). (2017).

[13] Narayanan, A., Abedini, A., Khameneh, F., & Butcher, C., An Experimental Methodology to Characterize the Uniaxial Fracture Strain of Sheet Metals Using the Conical Hole Expansion Test. Journal of Materials Engineering and Performance, 32(10), 4456–4482. (2023).

[14] Wang, K., Luo, M., & Wierzbicki, T., Experiments and modeling of edge fracture for an AHSS sheet. International Journal of Fracture, 187(2), 245–268. (2014).

[15] Pathak, N., Butcher, C., & Worswick, M., Assessment of the Critical Parameters Influencing the Edge Stretchability of Advanced High-Strength Steel Sheet. Journal of Materials Engineering and Performance, 25(11), 4919–4932. (2016).

[16] Dykeman, J., Malcolm, S., Yan, B., Chintamani, J., Huang, G., Ramisetti, N., & Zhu, H., Characterization of edge fracture in various types of advanced high strength steel. SAE 2011 World Congress and Exhibition. (2011).

The publication of this article was funded by the ETH Zurich 10.13039/501100003006