Original Article

Experimental evaluation of hole expansion ratio in DP600 steel sheet using a displacement controlled stopping criterion

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Abstract

This study presents the development and validation of an experimental procedure for determining the hole expansion ratio in DP600 steel sheets. The proposed method introduces a fracture criterion based on the observation of a single edge crack, characterized by one through-thickness fracture. The procedure was structured as a step-by-step algorithm inspired by numerical search strategies. The experimental application of the methodology led to the identification of a critical punch displacement of 9.52 mm, at which all tested samples exhibited exactly one complete fracture. The resulting hole expansion ratio values showed an average of 32.4% ± 0.2%, demonstrating good repeatability. The proposed method provides a precise and reproducible alternative for evaluating the formability and edge flangeability of sheared edges in hole expansion tests without automatic fracture detection systems.

Keywords: Hole expansion ratio; Fracture criterion; DP600 Steel; Edge formability.

1 Introduction

The automotive industry has undergone major transformation in recent decades, largely in response to increasingly stringent global regulations regarding fuel efficiency and greenhouse gas emissions. In this context, the demand for lightweight, high-performance materials has grown significantly. Advanced high-strength steel (AHSS) and aluminum alloy have emerged as key materials in vehicle design, offering a favorable combination of weight reduction and mechanical performance. Among these materials, AHSS are especially for safety-critical components due to their high strength and good energy absorption capacity [1].

However, the mechanical advantages of AHSS often come at the expense of reduced edge formability. During typical manufacturing sequences, such as punching, trimming, and subsequent flanging, sheet metal components may experience localized deformation near the sheared edges, which are susceptible to premature fracture. Microcracks, burrs, and hardened zones introduced during cutting processes frequently serve as crack initiation sites. In these cases, traditional formability criteria such as the Forming Limit Curve (FLC) are insufficient, as they do not account for localized edge damage [1,2].

To address this limitation, the Hole Expansion Test (HET), standardized by ISO 16630 [3], has become one of the most widely adopted methods for characterizing edge formability. The test involves expanding a pre-punched hole in a flat specimen using a conical punch until a through-thickness edge crack is detected. The HER is defined as the percentage increase in hole diameter before the onset of cracking and it is used as the quantitative indicator of the material's edge stretchability. The method is relatively simple, reproductible, and directly relevant to forming operations such as stretch flanging, hole flaring, and edge bending in automotive Body-in-White (BIW) assemblies [2]. Figure 1 shows the standardized procedure to determine the HER. The HER is calculated according to Equation 1:

$$HER=\frac{D_h-D_0}{D_0}\times 100 \quad (1)$$

Where D_0 is the standardized initial hole diameter (10 mm), D_h is the diameter of the deformed hole at the instant a complete through-thickness edge crack is detected.

Despite its standardization, the HET presents significant challenges that compromise its reliability. The method is highly sensitive to how the initial hole is prepared. Punched holes often introduce residual stresses, strain-hardened zones, and microscopic defects, while drilled holes usually result in high HER values due to their smoother edge finish [4-6]. Burr orientation also influences crack initiation, with burr-up configurations generally promoting earlier fracture [2,4]. Additionally, the stopping criterion of the test is traditionally determined by visual inspection, which introduces operator

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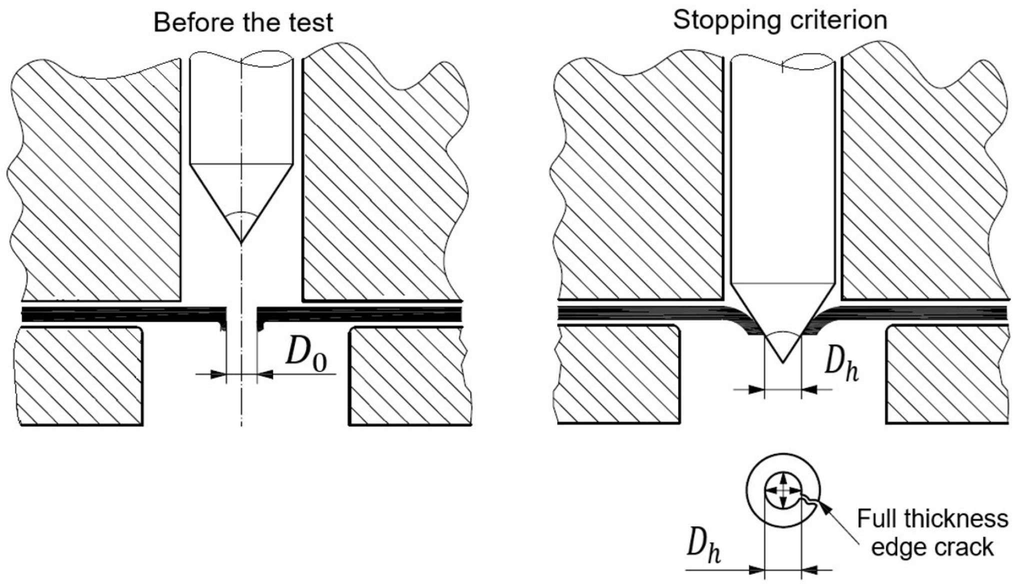

Figure 1. Schematic procedure of the hole expansion test, adapted from [3].

subjectivity and affects result repeatability [5,6]. Although techniques such as digital image correlation (DIC) and acoustic emission monitoring have been suggested as alternative, they are not yet standardized in ISO procedures [1,4,7].

Another critical point is that HER is affected by a complex interaction of factors beyond tensile strength of global ductility. Studies have shown that microstructural features, such as martensite distribution, grain morphology, and second-phase particles, can strongly influence crack propagation behavior at the edge. For instance, ferrite-martensite dual-phase (DP) steels often show lower HER than fully ferritic steels, due to the presence of brittle phase near the cut edge [1,6]. Trimming parameters, including punch-die clearance and velocity, also play a decisive role in defining the edge condition and local formability [4,7]. Cho et al. [8] and Pathak et al. [9] showed through microhardness tests for materials with a high fraction of martensite phase, such as complex phase and martensitic steels, the damage caused by the punch during shearing can significantly increase the hardness (on the order of 100 MPa) at the sheared edge. Due to the complexity associated with the forming process during the HET, it is difficult to predict the HER based solely on conventional mechanical properties, making experimental evaluation essential. Furthermore, accurate HER values are desired for calibrating damage models and validate numerical simulations of forming processes [6,7,10].

In this context, the present work proposes the development of and validation of a systematic experimental methodology for determining HER in DP600 steel. The method introduces an objective stopping criterion based on the detection of the first full-thickness edge crack, using an iterative approach inspired by numerical search techniques. This structured procedure aims to reduce operator subjectivity, enhance repeatability, and provide more robust input data for formability assessments and material development efforts in the automotive industry.

2 Materials and methods

2.1 Material

The experimental investigation was carried out using DP600 dual-phase steel sheets with a nominal thickness of 1.2 mm. This material is commonly used in the automotive industry due to its advantageous balance between mechanical strength and ductility. Its dual-phase microstructure, typically consisting of ferrite and martensite, makes it particularly sensitive to edge formability issues, especially under stretch-flanging conditions where crack susceptibility is high.

To ensure compliance with ISO 16630:2017, all specimens were prepared with a centrally located 10 mm diameter hole, created through mechanical punching. The holes were positioned at least 45 mm from the sheet edges and 90 mm apart from neighboring holes, minimizing the influence of boundary effects and stress interactions.

2.2 Equipment and test setup

Hole expansion tests were performed using a universal testing machine equipped with a custom-built fixture adapted from the device described by Santos et al. [2], and fully compliant with ISO 16630 specifications, Figure 2a.

The setup included a conical punch with a 60° ± 1° tip angle and minimum hardness of 55 HRC, a supporting die with an internal diameter of at least 40 mm and a 5 mm corner radius, and a clamping system to prevent sheet movement or material draw-in during deformation, Figure 2b.

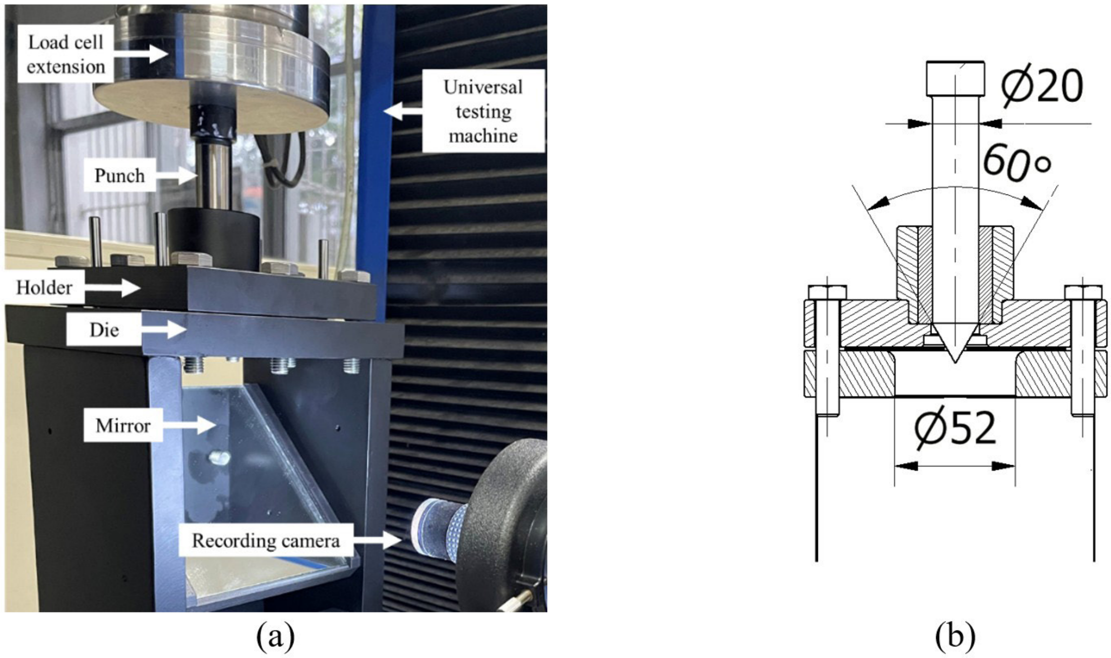

Figure 2. (a) Experimental setup for the HET and (b) tooling details [2].

To reduce friction between the punch and the specimen, a molybdenum disulfide (MoS_2)-based lubricant was applied to the contact surfaces. A mirror angled at 45° and a digital camera system were integrated into the apparatus to facilitate real-time visual monitoring of edge crack initiation during punch displacement.

All tests were performed at a constant punch displacement rate of 5 mm/min. The test was interrupted immediately upon the visual detection of a through-thickness crack on the hole edge.

2.3 Hole expansion test algorithm

To reduce the subjectivity associated with visual crack detection and improve test repeatability, a systematic experimental procedure, here referred to as an algorithm, was developed to determine the HER based on a well-defined fracture criterion: the occurrence of exactly one complete through-thickness edge crack, defined in the algorithm as a number of full cracks equal one (NFC = 1).

Although not a computational algorithm, the method was inspired by numerical search strategies such as bisection and fixed-step convergence. The approach aimed to identify the minimum punch displacement required to induce a single full crack, thus defining the limit of edge ductility with high reproducibility.

The overall structure of the algorithm is shown in the flowchart in Figure 3, highlighting the logic decision used to converge toward the critical displacement. The symbols used in the flowchart are described as follows: d_m represents the mean displacement tested during convergence, d_r is the critical displacement that results in an NFC equal to one. The initial hole diameters before expansion are denoted by D_0, and D_h is the final diameter after expansion, obtained by averaging the measurements at 0º and 90º regarding the sheet rolling direction.

The algorithm developed in this study was implemented in four sequential steps, namely, initialization, reduction, convergence, and validation. In the initialization step, an excessive punch displacement is applied to ensure at least one visible complete fracture, typically resulting in more than one full crack at the edge (NFC $\geq$ 2). The reduction step aims to determine the lower limit of the probability zone for a single fracture; for this purpose, the algorithm is applied iteratively until no edge fracture occurs (NFC < 1). The convergence step then seeks to identify the punch displacement that produces exactly one through-thickness fracture along the sheared edge (NFC = 1). Since the proposed methodology involves multiple samples, each potentially exhibiting slight variation in hole conditions, a validation step is required. In this final step, at least three samples are tested to confirm that the selected displacement consistently results in a single complete fracture. Then to calculate HER, the final hole diameter was measured in two orthogonal directions: 0° and 90° according to the sheet rolling direction (RD). The average of these two values was assumed as the D_h of Equation 1.

It is important to explain that although the critical displacement (d_r) is determined mechanically through controlled punch movement, the detection of NFC = 1 was conducted by macroscopic visual inspection of the specimen edge after testing, using a camera with 300×

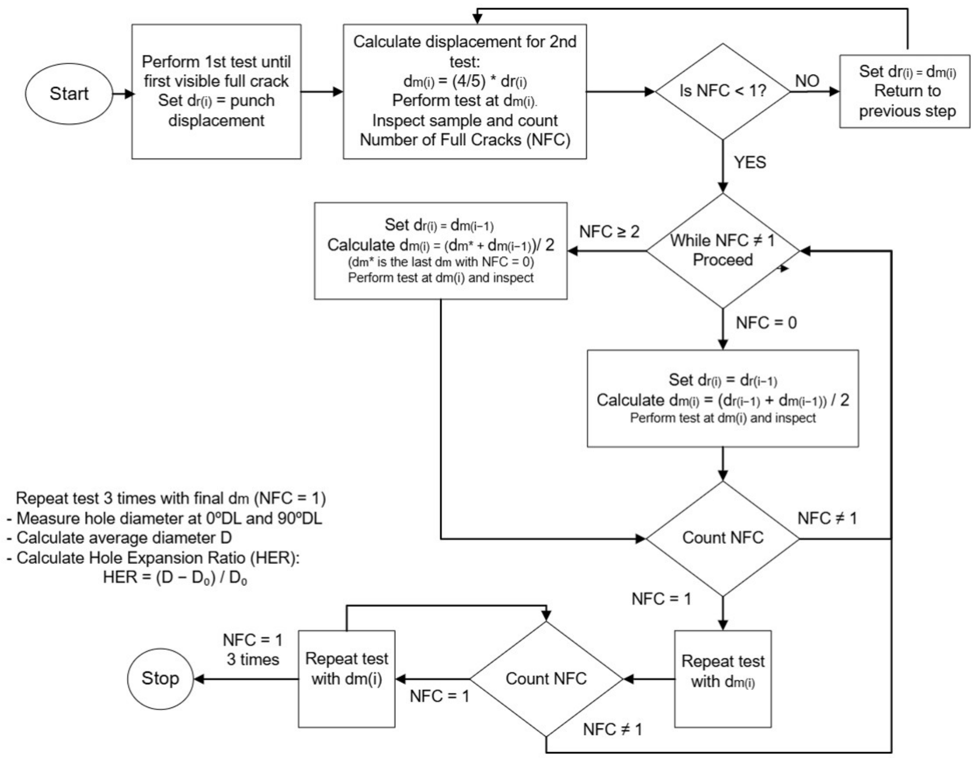

Figure 3. Flowchart of the hole expansion test algorithm.

magnification. To minimize subjectivity, this evaluation was based on a binary criterion: the presence or absence of a clearly visible, fully open through-thickness crack. This approach aligns with ISO 16630, which defines fracture as a crack that extends completely through the material thickness. Even using techniques to magnify the edge region, the visual inspection after hole expansion test to determine the number of complete fractures can be a nontrivial task.

This highlights the difficulty of applying the stopping criterion in the conventional method, in which the hole edge is in contact with the punch. The proposed procedure minimizes this issue by reducing the likelihood of operator-dependent measurement errors.

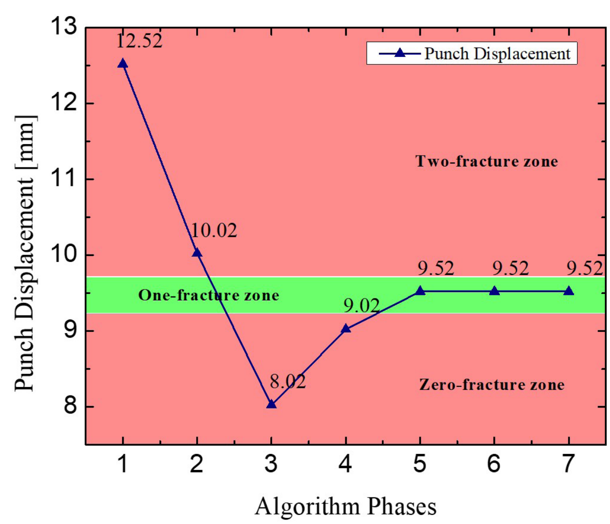

Figure 4. Algorithm Phases vs. Punch Displacement.

3 Results

3.1 Determination of the critical displacement

The algorithm developed in this study was applied to identify the critical punch displacement that consistently generates exactly one through-thickness edge crack (NFC = 1). Figure 4 and Table 1 presents the number of complete fractures observed for each specimen as a function of punch displacement.

This displacement lies between the over-expansion region (NFC = 2) and the under-expansion region (NFC = 0), confirming the transition point predicted by the algorithm.

Table 1. Number of Complete Fractures (NFC) per specimen and displacement

Specimen	Punch displacement [mm]	NFC
1	12.52	2
2	10.02	2
3	8.02	0
4	9.02	0
5	9.52	1
6	9.52	1
7	9.52	1

Table 2. Hole expansion measurement and her results

Specimen	D_0	D_f 0º	D_f 90º	D_f mean	HER
	[mm]	[mm]	[mm]	[mm]	[%]
5	9.93	13.15	13.10	13.13	32.2
6	9.90	13.15	13.10	13.13	32.6
7	9.88	13.10	13.05	13.08	32.4

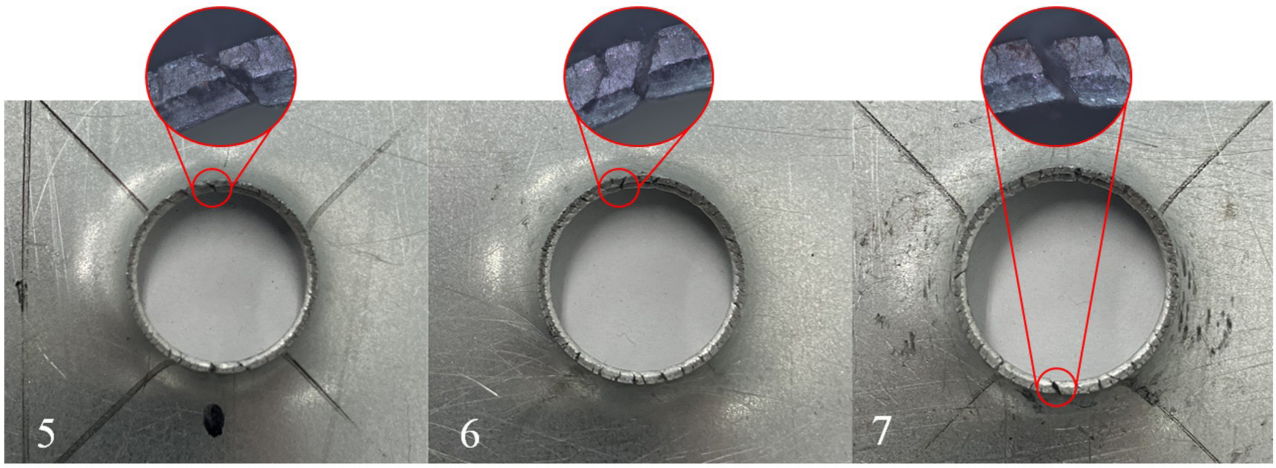

Figure 5. Top view of the tested specimens #5, #6 and #7 showing through-thickness cracks after Hole Expansion Testing at the critical displacement of 9.52 mm (NFC = 1).

Repetition of the test at 9.52 mm across three specimens yielded identical NFC = 1 results, demonstrating good repeatability.

3.2 Final hole diameter measurement and HER calculation

To validate the displacement-based HER determination method, three specimens were tested at the critical punch displacement of 9.52 mm, previously identified as the condition corresponding to exactly one through-thickness edge crack (NFC = 1). Visual inspection of the expanded holes confirmed the presence of a single macroscopic crack in each specimen, indicating consistency and reliability in the fracture behavior.

Figure 5 illustrates the tested specimens after hole expansion. Each central image shows the top view of the expanded hole, while the magnified insets highlight the typical through-thickness edge cracks that characterize the NFC = 1 condition adopted in this study.

Final hole diameters were measured along the rolling direction (0°) and the transverse direction (90°), and the HER was calculated using the average of these values. Table 2 summarizes the measured parameters and the resulting HER for each specimen.

The average HER obtained was 32.4%, with a standard deviation of ±0.2%, indicating consistent repeatability. These results are consistent with the values reported in the literature for DP600 dual-phase steel, thereby validating the proposed algorithm and test procedure.

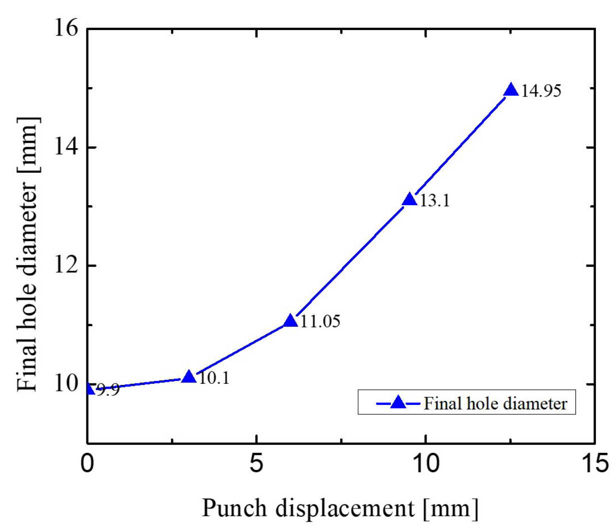

Figure 6. Final hole diameter as a function of punch displacement.

3.3 Correlation between punch displacement and final hole diameter

To assess the mechanical consistency of the deformation process, final hole diameters were plotted as a function of punch displacement. A near-linear trend was observed, as shown in Figure 6.

The direct correlation between displacement and final diameter supports the effectiveness of the proposed method, reinforcing that HER can be confidently calculated from standardized displacement conditions that correspond to the onset of fracture.

4 Discussion and conclusion

This study presented the development and validation of a systematic experimental methodology for determining the HER in metallic sheets, with a specific application to DP600 dual-phase steel. The proposed approach introduces an objective stopping criterion based on the detection of a single complete through-thickness crack (NFC = 1), enabling a more consistent and reproducible evaluation of edge formability.

By employing a structured, stepwise convergence algorithm inspired by numerical search strategies, the methodology successfully identified the critical punch displacement of 9.52 mm as the condition associated with the onset of fracture. Validation tests demonstrated good repeatability, with all specimens exhibiting exactly one full-thickness edge crack. The corresponding HER values averaged 32.4% ± 0.2%.

A nearly linear relationship was also observed between punch displacement and final hole diameter, confirming the mechanical consistency of the deformation process and supporting the validity of displacement controlled HER evaluation. Compared to conventional methods prescribed in ISO 16630, which often rely on subjective crack detection and suffer from variability in specimen preparation, the proposed methodology offers significant improvements in terms of accuracy, robustness, and statistical confidence.

Determining the exact moment of a complete edge fracture during a hole expansion test is a challenging task, even for experienced professionals using advanced equipment. Automatic fracture detection can be affected by several factors, such as lighting conditions, material characteristics, and equipment resolution [11,12]. The proposed methodology identifies the region with the highest probability of edge fracture occurrence based on punch displacement. Compared to the traditional method, this approach requires a slightly larger number of samples (fewer than ten); however, it enables a more accurate determination of the hole expansion ratio, minimizing operator-dependent errors when automatic fracture detection is not available.

The approach developed in this work can be readily adapted to other advanced high-strength steels and metallic alloys, and has potential applications in laboratory testing, quality control, and numerical model calibration. Future studies may extend this methodology to assess edge damage sensitivity in more complex material systems or under different cutting and trimming conditions.

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