Stretch flangeability of AHSS automotive grades versus cutting tool clearance, wear, angle and radial strain gradients

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Abstract. Stretch flangeability tests are performed on cold rolled AHSS automotive steel grades for crack sensitivity evaluation. The ISO16630 tests procedure is used with different cutting edge conditions including cutting clearance, cutting tool wear, cutting tool angle and hole expansion punch tool geometry. Among all influence parameters, the cutting clearance is considered to be the most critical to control. Low (<10%) and high (>20%) clearances are significantly detrimental to hole expansion ratio (HER). An optimum in HER is reached around 15% clearance. Both cutting punch wear and cutting die wear each affect negatively the HER values in comparison to new sharp cutting tools. Varying the cutting angle with concave and convex hole punching tool geometries in stead of orthogonal cutting has a rather negative effect on stretch flangeability due to irregular cut edge quality along hole perimeter and excessive tool wear in the concave configuration. The influence of hole expansion punch geometry (flat R25, biaxial Nakajima R25 vs. ISO16630 60° conical) on the HER values is also investigated. The (true) HER values are proportional to the FE simulated logarithmic radial strain gradient at fracture.

1. Introduction

Advanced High Strength Steels (AHSS) are widely used in the automotive industry, driven by vehicle weight reduction and crash safety requirements. Their reduced shear edge formability however is a growing concern [1]. Shear edge failure may occur for strain levels much lower than the forming limit curve (FLC) depending on the steel grade considered [2]. The conical hole expansion test, as described in the ISO 16630 procedure [3], is suitable to characterize the stretch flangeability of steel grades.

Among all influence parameters, the cutting clearance is considered to be the most critical for stretch flangeability control. High cutting clearances are advised to avoid crack formation after hole expansion test in AHSS [4]. Nominal clearances ≥ 12% can be considered as long as burr formation is not occurring [4]. Own investigations on AHSS confirm an optimal clearance between 12% and 20% for optimum hole expansion ratio (HER) [5]-[6]. Current AHSS processing guidelines suggest adapted clearances according to sheet strength and thickness level [7]. Optimal HER values for higher strength and thickness sheet steels require an increase of cutting clearance from typically ≈8% for mild steels up to ≈15% for AHSS [7].

Close monitoring of cutting tool wear is also necessary for edge crack minimizing [7]. A significant decrease of HER values from 25% with a sharp punch down to 16% for a worn out cutting punch has been observed in [8] for a DP980 steel grade. Significant negative tool wear effects on stretch flangeability of AHSS are also found in [9] for hot rolled HDT780C steel. An increase of punch radius
as well as die radius up to 250µm both decrease the HER values. A combination of both punch and die tool wear together has an even worse influence on HER values degrading from 80% down to 30% [9].

HET investigations have been performed in [10] for DP980 and DP1180 with flat, conical and roof top cutting punches. Flat expansion HER values are similar for flat and conical cutting punch geometries and worse for roof top cutting punch configuration. Investigations in [11] for DP600 and DP980 show the positive influence of angled straight edge cutting on edge crack strain values with an optimum for 6° lower/upper blade angle as well as 3° rake shear angle at 15% clearance. Similarly a 6° bevel or conical cutting punch yield the best conical HER values for DP600, DP800 and DP1000 steels in [12].

Some investigations also suggest that the strain gradient (radial curvature of hole edge during expansion) influences significantly positively the HER values [13]-[17]. The radial strain gradient can be influenced by varying the conical expansion tool angle and initial hole diameter [13]. The use of hemispherical Nakajima punches influences also the radial strain gradient amount at cut edge [14]. According to [15] this strain gradient might effectively suppress local neck formation and have a positive influence on the limiting edge crack strain. This radial strain gradient is stronger for 60° conical and hemispherical punches compared to a flat punch [15]. A linear positive dependency of edge crack strain versus radial strain gradient is clearly shown in [16]-[17]. Different hole diameters from 10 to 50mm combined with 50-60° conical punches as well as Nakajima and Marciniak punches are varied to achieve a large range of strain gradient at hole edge in [16]-[17]. Even elliptical holes have been used to clarify the (small) influence of tangential major strain gradients along hole edge on HER values [17].

The stretch flangeability of AHSS cold rolled steels cut edges is determined in the present work based on the 60° conical ISO16630 hole expansion test set up (HET) with different cutting clearance (5-40% range), cutting tool wear conditions (sharp/worn shear punch/die) and punch cutting angle (concave, convex, orthogonal). Additionally flat and hemispherical hole expansion punch geometries have been compared with the ISO standard conical punch geometry for strain gradient analysis.

2. Experimental procedures

2.1. Investigated materials

Following cold rolled AHSS grades (CR) in the thickness range between 0.8mm and 1.5 mm have been investigated: a dual-phase steel (DP1000) and two complex phase steels, CP1000HD and CP1200. Table 1 shows their transverse mechanical properties according to ISO6892-1 standard [18] using specimens type 2 with a reference gage length of 80 mm.

| Steel grade designation       | t (mm) | Rp02 (MPa) | Rm (MPa) | A9 (2%) | A90 (5%) | nA9 | r4   |
|--------------------------------|-------|------------|----------|---------|---------|-----|------|
| DP1000 (CR700Y980T-DP-UC-U)   | 0.8   | 735        | 1074     | 7.5     | 10.5    | 0.073 | 0.94 |
| CP1000HD (CR780Y980T-CH-UC-U) | 1.5   | 909        | 1062     | 7.1     | 10.7    | 0.068 | 0.96 |
| CP1200 (CR900Y1180T-CP-GI50/50-U) | 1.5 | 1079      | 1215     | 5.1     | 8.3     | 0.049 | 0.92 |

2.2. ISO 16630 standard conical hole expansion test

Figure 1 shows schematically the 60° conical ISO 16630 hole expansion test (HET) setup. The limiting hole expansion ratio at first through-thickness crack (HER) is expressed in % as the ratio of hole diameter expansion to the original hole diameter as follows [3]:

\[ HER = \frac{D_h - D_0}{D_0} \times 100 \]

(1)

with \( D_h \): average hole diameter at first through-thickness crack; \( D_0 \): initial (10mm) hole diameter.
All tests are performed in the burr-up configuration (burr on die side) at 12% cutting clearance with a 60° conical punch and 10mm initial hole diameter according to ISO 16630 standard. The tests are stopped manually without optical magnifying device at first through-thickness crack (Figure 1). The final hole diameter is measured with a caliper in unloaded condition at two locations away from edge crack according to ISO 16630 procedure.

![Figure 1. ISO 16630 Hole expansion HET test setup.](image)

Table 2 shows the hole expansion ratio in punched 12% clearance and drilled condition of the investigated materials (mean and standard deviation). HER values are higher in the drilled than punched condition, since this process minimizes material damage around hole perimeter in comparison to shear cut edges.

| Steel type | Steel grade | Punched Conical HER, $\lambda$ [%] | Drilled conical HER, $\lambda$ [%] |
|------------|-------------|-----------------------------------|-----------------------------------|
|            |             | Mean | Standard Deviation | Mean | Standard Deviation |
| Cold rolled| DP1000      | 37   | 4                  | 48   | 7                  |
| CP1000HD   | 86          | 5    | 2                  |
| CP1200     | 67          | 5    | 8                  |

2.3. Alternative hole expansion test punch geometries
Additional hole expansion tool geometries have also been investigated (flat R25, hemispherical Nakajima R25 vs. 60° conical ISO16630 punch) with a 10mm hole diameter in punched vs. drilled condition (Figure 2). This way some more in plane hole expansion load configuration can be simulated.

![Figure 2. Hole expansion punch geometry (conical, hemispherical, flat).](image)
2.4. Test program overview
In the following chapter different parameters on conical hole expansion ratio have been investigated such as cutting clearance (chapter 3.1), cutting tool wear (chapter 3.2) and cutting tool angle (chapter 3.3). The influence of strain gradient during subsequent hole expansion has also been investigated with different punch geometries (chapter 3.4). Wherever suitable an investigation on cut edge parameters with a 360° panoramic optical hole edge inspection system is also given. All chapters should be considered as independent investigations and are not necessarily interconnected.

3. Results and discussion

3.1. ISO16630 conical hole expansion ratio vs. cutting clearance
The influence of punching clearance on hole expansion ratio (HER) based on ISO16630 test procedure is shown in Figure 3 in the 5-40% cutting clearance range. The drilled HER values are given as reference. Low (<10%) and high (>20%) clearances are significantly detrimental to hole expansion ratio. An optimum in HER is reached around 15% clearance. Those results are consistent with previous HER vs. clearance findings in [4]-[6] and AHSS processing guidelines for stretch flangeability optimization [7].

Figure 3. ISO 16630 hole expansion ratio vs. cutting clearance and for drilled condition.

3.2. Cutting clearance vs. rollover height
Figure 4. (a): Cut edge parameters definition; (b): Cutting clearance vs. rollover height.
Figure 4a shows the definition of cutting parameters such as rollover, burnish, fracture and burr expressed in % fraction of material thickness. At low clearance a distinction is made between primary and secondary burnish (as well as primary and secondary fracture).

The cutting clearance is directly linear proportional to rollover height clearance (and vice versa) for a given material, thickness and cutting tool (Figure 4b). The higher the material stiffness (strength and thickness), the lower the rollover bending amount. The proportionality of rollover and clearance maybe helpful in industrial condition. The effective cutting clearance in components could then be calibrated easier directly from rollover height without the need for metallographic sections. Since cutting clearance is a key parameter in stretch flangeability control, such rollover-clearance correlation should be helpful.

Cut edge investigations vs. cutting clearance show the emergence of local geometrical notches within punched edge such as secondary burnish at low clearance (Figure 5a) or excessive burr combined with a rough stair step like fracture shape at high clearance (Figure 5b,c).

Secondary burnish, as defined in Figure 4a, occurs for the investigated AHSS steels at clearance below ~8% and is correlated with a decrease in HER values at low clearances (Figure 6a). Burr is found above ~25% clearance and is also linked to a reduction in HER values at high clearances (Figure 6b).
HER values are maximum at 15 ± 5% clearance when burnish values are minimum (Figure 7a), fracture height values are maximum (Figure 8a) and burnish to fracture ratio are minimum (Figure 9a). HER values generally increase with decreasing burnish height (Figure 7b), increasing fracture height (Figure 8b) as well as decreasing burnish to fracture ratio (Figure 9b).

HER values are maximum for burnish values around 15% for DP1000, 20% for CP1000HD and 25% for CP1200 (Figure 7). HER values are optimum for fracture height values around 75% for all investigated steels (Figure 8). HER values are also maximum for burnish to fracture ratio values around 20% for DP1000, 30% for CP1000HD and 35% for CP1200 (Figure 9).

![Figure 7](image7.png) (a) Burnish height & HER vs. clearance; (b) HER vs. burnish height.

![Figure 8](image8.png) (a) Fracture height & HER vs. clearance; (b) HER vs. fracture height.

![Figure 9](image9.png) (a) Burnish to fracture ratio & HER vs. clearance; (b) HER vs. burnish to fracture ratio.
3.2. ISO16630 conical hole expansion ratio vs. cutting tool wear

The cutting tool wear has been experimentally reproduced for CP1000HD and CP1200 at 9.6% and 12.2% clearance with various tool wear conditions. Two punching tool configurations have been chosen: a new punch with 30±10µm radius and a worn out punch with 50±10µm punch radius naturally abrasively rounded off after ≈ 3000 strokes. Two cutting die configurations have also been investigated: a new cutting die with 20±10µm radius and a manually grinded cutting die with 200±30µm radius. According to industrial feedback a large 200µm die radius is a realistic worst case. The punch tool wear with a 50µm edge radius seems rather representative of natural abrasive wear after a few 1000 strokes.

Figure 10 shows the corresponding hole expansion ratio (HER) values results. Both cutting punch wear and die wear affect negatively the HER values. This effect seems to increase with increasing cutting clearance (9 to 12%). A combination of both punch and die wear is additive and can lead to a significant cumulative worst case HER decrease in comparison to new sharp cutting tools configuration (≈90% to 55% for CP1000HD, ≈70% to 50% for CP1200 for 12% clearance). Similar effects have been reported in [7]-[9] for AHSS grades.

Cutting tool wear with increased punch and/or die radius leads to a minimal increase in rollover, a significant increase in burnish height and a decrease in fracture height. Tool wear is also inducing burr generation at large cutting die radii (200µm).

As shown in Figure 11 for CP1000HD and CP1200, the HER values correlate with the amount of burnish or fracture height. Burnish increases and fracture height decreases with increasing tool wear for a given clearance. Burr appears only for large die radii, which additionally lowers the HER values.

![Figure 10](image1.png)
**Figure 10.** HER vs. cutting die & punch radius and clearance. (a): CP1000HD; (b): CP1200.

![Figure 11](image2.png)
**Figure 11.** Cut edge parameters vs. tool wear & clearance. (a): CP1000HD, (b): CP1200.
Figure 12 shows a clear linear dependency of HER values vs. burnish or fracture height (Figure 12a) and burnish to fracture ratio (Figure 12b) when all tool wear data are plotted together (CP1000HD vs. CP1200, 9.6% vs. 12.2% clearance, for all investigated tool wear conditions). Such cut edge parameters could be therefore suitable indicators for tool wear monitoring in production lines.

3.3. ISO16630 conical hole expansion ratio vs. cutting angle

Literature work is increasingly found to improve HER values by punching tool geometry optimization [10]-[12]. The ISO16630 classical punching configuration prescribes a 10mm hole diameter punched with an orthogonal 90° punching angle [3]. Additionally, concave and convex punch geometries have been investigated as shown in Figure 13. The convex roof top punch shape is flat in the bottom middle with a 17° angle on both sides. The concave bottom punch shape is flat on the outer regions with a 5mm radius hollow shape in the center. Figure 14 shows the influence of punching tool geometry on conical HER values. Figure 15 shows exemplarily for CP1000HD the effect of orthogonal, concave and convex punch on cut edge (360° panoramic pictures with an optical cutting edge inspection tool).

A positive effect on HER values could not be found using such alternative shear punch geometries (Figure 14). Contrary to orthogonal cutting, the cutting clearance is inhomogeneous along hole perimeter for concave and convex punch geometries, the amount of rollover and burnish varying sharply along hole perimeter (Figure 15). At some symmetric cut edge locations burnish vanishes with an unusual direct transition between rollover and fracture zone. The local cutting clearance is undefined either too low or too high, which is in both cases detrimental to HER ability of the punched material in comparison to an homogeneous orthogonal cutting tool.
The punch tool wear is also massively increased through early chipping after only 22 strokes for the concave hollow punch shape as shown in Figure 13b. This is due to excessive notch stress concentration level in this hollow concave configuration at the transition between flat and curved punch regions. Higher tool material grades and heat treatment are needed for such elaborated punch geometries [12].

Figure 14. ISO 16630 HER ratio vs. cutting tool geometry (orthogonal, concave, convex).

Figure 15. Cut edge 360° morphology vs. cutting tool geometry (CP1000HD).

3.4. Hole expansion ratio vs. expansion punch geometry and radial strain gradient

The influence of hole expansion punch geometry (flat R25, Nakajima R25 vs. ISO16630 60° conical) on the HER values in punched (12% clearance, 10mm hole diameter) vs. drilled condition has been investigated (Figure 2). The tests are simulated with LS DYNA (shell elements, friction coefficient 0.1, Barlat anisotropy model, flow curves based on tensile and bulge tests, no damage model). The experimental HER values are chosen as fracture criteria for the FE simulation and the linear radial logarithmic major strain gradient up to 2-2.5mm transverse from hole edge are determined.

The HER results are given in Figure 16. Figure 17a shows exemplarily the method for determining the logarithmic radial strain gradient at HER level. Figure 17b shows an overview of testing results including all materials, hole conditions and punch geometries. The logarithmic HER values are linear proportional to the logarithmic radial strain gradient, in agreement with previous literature investigations [13]-[17], the strain gradient sensitivity being defined as the slope of log. HET vs. log. radial strain gradient is highest for CP1200 and CP1000HD with values around 4 double as high as for DP1000 (≈ 2). CP grades are known to be more sensitive to sheet curvature bending effects [5], [13]-[14]. Such HER-strain gradient information in Figure 17b may be implemented in FE postprocessing for safe assessment of HER values depending on the local flange geometry of components.
Figure 16. Conical HER vs. expansion punch geometry. (a): punched hole; (b) drilled hole.

Figure 17. FEM Log. major strain gradient vs. HER level. (a): strain gradient method from last 2-2.5mm \( \varepsilon_{MAJ} \) from edge; (b): results overview in punched and drilled conditions.

4. Conclusions

Following conclusions can be drawn from this investigation:

- **Conical ISO16630 HET**: The superiority of complex phase with regard to conical hole expansion ratio is clearly shown both in punched (12% cutting clearance) and drilled conditions.

- **HER vs. cutting clearance**: Among all influence parameters, the cutting clearance is considered to be the most critical factor to consider and control. Low (<10%) and high (>20%) clearance are significantly detrimental to hole expansion ratio. An optimum in HER is reached around 15% clearance for AHSS. Sharp local geometrical notches within cut edge such as secondary burnish at low clearance or excessive burr, combined with a rough fracture shape at high cutting clearance should be avoided for stretch flangeability improvement.

- **HER vs. tool wear**: Both cutting punch wear and cutting die wear affect negatively the HER values. A combination of both punch and die cutting tool wear can lead to an even more significant HER decrease in comparison to a new sharp cutting tool configuration (HER \( \approx \)90% to 55% for CP1000HD, HER \( \approx \)70% to 50% for CP1200 at12% clearance). Cutting tool wear with increased punch and/or die radius leads to a minimal increase in rollover, a significant increase in burnish and a decrease in fracture height. Some burr appears at high cutting die radii. The influence of cutting tool wear (punch and die) together with the knowledge of exact cutting clearance should therefore be considered in
the early component design phase. A close online monitoring of burnish to fracture ratio may deliver some information about cutting tool wear evolution in production lines.

- **HER vs. cutting angle:** A positive effect on HER values could not be found using alternative concave and convex hole punching tool geometries. Contrary to orthogonal cutting, the cutting clearance is irregular along hole perimeter for concave and convex punch geometries, the amount of rollover and burnish varying sharply along hole perimeter, which is detrimental to HER ability. The cutting punch tool wear is also massively increased for the concave hollow punch shape.

- **HER vs. radial strain gradient:** The influence of hole expansion punch geometry (flat R25, Nakajima R25 vs. ISO16630 60° conical) on the HER values in punched (12% clearance, 10mm hole diameter) vs. drilled condition has been investigated. The varying radial strain gradient at fracture has been determined with FE Simulation. The (true) hole expansion ratio values are proportional to the logarithmic radial strain gradient. The strain gradient sensitivity is the highest for CP1200 and CP1000HD twice as high as for DP1000. This non negligible radial strain gradient effect should be therefore implemented in stretch flanging FE simulations for early edge crack detection warning.

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