Influence of cutting tool stiffness on edge formability

E. Levin¹, P. Larour², M. Heuse³, D. Staupendahl¹, T. Clausmeyer¹ and A. E. Tekkaya¹

¹ Institute of Forming Technology and Lightweight Components, TU Dortmund University, Baroper Str. 303, 44227 Dortmund, Germany
² voestalpine Stahl GmbH, voestalpine-Straße 3, 4020 Linz, Austria
³ Faurecia Autositze GmbH, Nordsehler Straße 38, 31655 Stadthagen, Germany

E-mail: Till.Clausmeyer@iul.tu-dortmund.de

Abstract. For the evaluation of the forming behaviour of cut edges of AHSS the Hole Expansion Test (HET) standardized in the ISO 16630 is generally used. However, the observed Hole Expansion Ratio (HER) is prone to significant scatter. One reason for this scatter is the subjective observation of the through thickness crack by the machine operator. Additionally, the ISO is not very specific in its description of the test setup and material preparation, actually allowing great variations in the cutting process. Although the nominal cutting clearance is specified, a low stiffness of the punching machine or tool can cause a non-uniform clearance along the circumference. Additionally, an oblique position of the punch can cause an angled or eccentric sheared hole, resulting in additional crack initiation sites on the shear cut surface. FE simulations are used to investigate the stiffness effects of a C-frame press design. A comparative round robin analysis based on ISO16630 was performed by cross-testing both cutting and hole expansion setups for a high strength hot rolled steel grade. Significant differences were registered in the HER values, whereby the cutting process was identified to have the largest influence on HER variation. The homogeneity of the burnished zone along the circumference was observed to give valuable information about the cut edge quality and subsequent level of HER values.

1. Introduction

The local formability of steel grades is more and more in focus and leads to development of specialized grades for dedicated applications like bending, hole expansion, flanging etc. [1]. The FLC provides only some predictions on global formability for restricted formability conditions like dome stretching but not for local formability issues like hole expansion, edge stretching, flanging, bending or compression loading[1]. The aspects of local vs. global formability are increasingly considered in the frame of the VDA239-100 global standard [2] for a classification of automotive steel grades [3].

Some research work is currently made to implement the reduction of fracture area (Z-value) in tensile tests for flat cold/rolled sheets for an assessment of the local formability of advanced high strength steels (AHSS) [4],[5]. The hole expansion test (HET) according to ISO 16630 standard, however, still remains the first choice for local formability issues such as cutting edge sensitivity for different materials [6]. This stretch flangeability test suffers unfortunately from a poor repeatability and reproducibility within and between test laboratories [7]. This test scattering hampers the efforts of steel suppliers and OEM’s to reliably evaluate the AHSS performances [8].

The aim of this study is to quantify the influence of the hole expansion experiment itself and the punching process on the determined HER. A 800MPa tensile strength hot rolled 2mm steel grade is used.
in this investigation. Different steps, i.e. punching of the hole and performance of HET, which are necessary to conduct HET are performed at different sites. A closer look is taken in this investigation on the cutting tool devices differing most obviously between both laboratories.

2. Literature review

The ISO16630 hole expansion test has some unique feature of consisting in a first 10mm hole shear cutting operation with 12% cutting clearance followed by the actual conical hole expansion until first through thickness crack [6]. This testing method contains a multitude of testing parameters both at shear cutting as well as in the hole expansion testing itself.

On the hole expansion testing level following parameters play more or less a role: punch drawing speed, alignment of hole and conical punch, lubrication of sample/punch, blank holder force level (draw-in), punch and die diameter, crack detection criteria (operator vs. video instrumented), delay between hole punching and hole expansion testing as well as some unavoidable intrinsic material scattering on a local microstructure level etc... Hole expansion investigations in [7] and [8] give a better overview on this complex topic, which will not be addressed within the present investigation.

On the hole shear cutting level the main challenge consists in reproducing a defined cut edge shape with similar cut edge parameters (rollover, burnish, fracture and burr height) prior to a subsequent edge formability testing. Many punching parameters are involved such as: cutting speed, cutting depth, lubrication type and amount, coaxiality and stiffness of cutting tools, effective clearance level and tolerances, cutting tool wear condition, cutting tool material, coating of cutting tools, press design, punching tool design (4-, 2-column, C-type frame), punching and testing on the same machine or separated etc... Such hole punching parameters influence hole expansion ratio (HER) values significantly and are recently subject of deeper investigations.

In [8] a round robin showed the variety of punching tools available for HET holes (from C type tool up to 4 columns). Sometimes lubrication (one drop) was used prior to hole punching. The hole punching speed varies widely between 6 and 124mm/s with either mechanical or hydraulic presses.

In [9] the focus was laid on the exact documentation of the effective cutting clearance by exact measurement of punch and die diameter as well as sample thickness. Since cutting clearance is a dominant parameter for the HER values especially for AHSS, some efforts have been put in the accurate clearance determination and documentation. The coaxiality of cutting clearance is also not necessarily fulfilled around the hole perimeter depending on the tool stiffness and design [9]. The non coaxiality of hole cutting clearance has also been observed in other hole expansion investigations even with much more sophisticated punching tools for aluminum 6111-T4 in [10] or TRIP800 steels in [11]. Crack location later on in the hole expansion test occurs rather at the location of reduced cutting clearance [11].

Measurements of the punch-die misalignment were performed in a controlled manner with micro-adjustment screws in the die holder in [12]. The final position validation was made optically with a LED light source at the punch side and a high-speed camera at the die side to track the clearance misalignment. A punching process with automatic centering with a moving die was also developed in [13] for cold punching of hot-stamped parts. Even for a small clearance, the punch and die become concentric due to the shift of the moving die by imbalanced force.

If too little clearance exists locally, secondary shear takes place, which results in poor quality of the blanked product [14]. Ideally, the die clearance is evenly distributed around the punch. In order to manufacture a press tool, tolerances are assigned to various dimensions of the press tool parts. Due to the cumulative effect of these tolerances, the condition of even distribution of die clearance can never be achieved in practice. Reducing the offset calls for tightening the tolerances of the press tool parts, which clearly results in an increase in the manufacturing cost of the press tool assembly [14].

Proper punch and die alignment is therefore a number one concern in tooling design. When a punch and die are not in line, the punch will deflect to one side leading to uneven shear, break, rollover, and burr in the pierced hole together with aggravated punch and die tool wear, galling up to chipping and punch breakage on the side with the tighter clearance [15]. In many cases, uneven clearance through lateral deflection of cutting punch will also cause the slugs to tip and interfere with stock feeding. The
best place to address the problem of lateral deflection is in initial design. Once the die is built, it is
difficult to resolve the problem [16]. A mapping of the shear cutting pre-straining to hole expansion test
in FEM-simulation has been recently performed at IUL in [17]. This, however, requires some knowledge
of a reproducible shear cut edge condition along hole circumference.

The ISO16630 requirement of 12% cutting clearance clearly should be fulfilled not only on average,
but also locally as much as possible, which is a practical challenge. This investigation, therefore, focuses
more specifically on the stiffness and coaxiality of cutting tools and cut edge parameters.

3. Hole punching and expansion experimental procedures

Table 1 summarizes the test parameter of the hole expansion comparison, with all parameters lying
within ISO16630 specifications. The material investigated is a commercially available hot rolled &
pickled 2.0mm steel with approximately 800MPa ultimate tensile strength. Samples have been punched
and tested in the as delivered non lubricated condition. The HET tools were cleaned with a cloth before
the testing series. The cutting clearance has been checked carefully based on real measured die and
punch diameter to be as comparable as possible within ISO 12% ±1% specification (11.75% at testing
lab 1 vs. 12.5% at testing lab 2). Figure 1 shows schematically the hole expansion test setup in the burr
up condition until first through crack occurrence.

| HET Testing laboratory | Lab 1 | Lab 2 |
|------------------------|-------|-------|
| Sample preparation     |       |       |
| Number of tests        | 10    | 10    |
| Sample size            | 130mm x 130mm | 200mm x 200mm |
| Lubrication of sheet sample | as delivered condition: hot rolled & pickled (no lubrication or degreasing of sample surface) |
| Cutting tool           | C-type | 2 columns type |
| Hydraulic 600kN bending press | Hydraulic 1000kN press |
| Diameter of punch      | 9.99mm | 10.01mm |
| Punch material         | Tool steel HSS >60 HRC | 1.3343 (HSS) |
| Diameter of die        | 10.46mm | 10.51mm |
| Cutting clearance      | (10.46-9.99)/2; 2.0 ± 11.75% | (10.51-10.01)/2; 2.0 ± 12.5% |
| BHF (Blank hold force) | not determined | no sample / cutting tool lubrication before punching |
| Lubricant              |       |       |
| Punching speed         | ±10±15mm/s | ±12 mm/s |
| Tip angle of punch     | 60° conical | 47°4mm |
| Diameter of punch      | Ø50mm | Ø74mm |
| Material of punch      | Tool steel 60 HRC±2 | 1.2379 |
| Diameter of die        | 56.6mm | 105mm |
| Punch-die clearance    | (56.6-50)/2; 3.2mm | (105-74)/2; 15.5mm |
| Die radius             | 9mm | 10mm |
| Material of die        | 6HRC±2 | 6HRC |
| Lubricant              |       |       |
| Hole expansion         |       |       |
| BHF (Blank hold force) | 4000kN | 4500kN |
| Testing speed          | ~0.5mm/s until crack occurs, slowing down speed to 0.1mm/s in crack vicinity | constant 0.1mm/s |
| Crack detection        | visual (unaided eye) stop at first through full thickness crack |       |
| Time between punching & testing | ~15min | ~4hrs |
| Final hole diameter    | after unloading, manual, using a calliper | after unloading, manual |
| measurement method     | 2 perpendicular directions with 45° inclination from crack | measurement with a 3-point micrometer |

A C-Type hole punching tool is used in a 600kN bending press in lab 1 (Figure 2). Bending moments
at the force application point as well as no coaxiality up to 0.2mm between punch and die have been
observed for this punching tool (Figure 2a). The punching tool of lab 2 is designed with 2 columns
guided upper (head, retainer) and lower (die and ground) plates within a 1000kN hydraulic press with 4
blank holder gas pressure springs (Figure 2b) to provide for stiffness and stability. The cutting tool wear
condition of both tools is comparable and acceptable.
**Figure 1.** ISO 16630 conical hole expansion test setup.

**Figure 2.** Testing tool setup (a) C-press tool at lab 1; (b) tool on hydraulic press with 2 guides at lab 2; tool wear condition (c) at lab 1, (d) at lab 2.

### 4. FE-Analysis of cutting tools

Several FEM stiffness analyses based on C-type punching tool have been performed for different relevant load cases in order to determine the machine and tool deflections under operation conditions. In particular, the effect of the return spring and off-center force application are investigated. The FEM-module in CATIA VX was used. The material behaviour is considered to be linear isotropic elastic with Young’s modulus of 210GPa and Poisson ratio of 0.3. The tools and machine components are discretized with tri-linear hexahedral elements. An implicit solver is selected.
The guides of the C-punch are sufficiently large to carry the applied punching forces. However, application of off-center forces (in \( y \)-direction) may lead to lateral deflections (in \( y \)-direction). In this configuration, the two guides lie in the same plane as the frame. As a result, this structure is sensitive to lateral / transverse forces. Figure 3 shows the results for two load cases, whereby the stiffness of the model is analyzed by displacement vectors at the model points.

Figure 3a shows the effect of the load on the frame by the return spring. The applied force in this simulation acts evenly distributed over the entire punch head. To simulate the spring a force of 500N was applied. The lowest point of the punch relative to the \( z \)-axis is marked with a black dot. The displacement of the punch in the sheet metal plane (\( xy \)-plane) of up to has a negligible value of 5\( \mu \)m.

Figure 3b shows the result of a simulation for which the applied maximum punching force (40kN for the examined steel grade) is not centered. As a result of the transverse forces, a bending moment of larger magnitude than in Figure 3a acts on the upper region of the frame. The displacement vector at the lowest point of the punch (the black dot in the image) shows much larger displacement values in the \( x \)- and \( y \)-axis (0.336; 0.307), thus resulting in a displacement of the punch by 0.46 mm.

The bending of the C-frame as a result of return springs can be considered as negligible. The lateral deflection of punching tool is however predominant. An offset in force application point on the punch head can lead to a lateral deflection of punching tool at maximal punching force of up to 0.46mm. Since the exact centering and alignment of the location of force application and the location of the punched hole depend on the clearances between different components of the tool, much higher tolerances are required to ensure a high punch quality with the C-frame press. Such lateral deflection effects are prevented with the 2 columns tool at lab 2, for which the force application occurs through well guided horizontal plates.

5. Cutting edge parameter analysis
A strategy for the preparation of the specimen and the experiment was developed for the two labs.

5.1. Cut edge parameters from metallographic sections
Some representative cut holes have been wire-cut perpendicular to cut edge, polished without etching and embedded for Light Optical Microscope investigations for both laboratory punching tools with 2 replicates each before hole expansion testing (Figure 4a). The amount of rollover, burnish fracture and burr as well as local clearance have been determined from each metallographic sections and plotted in 90° steps over the section angle to rolling direction (Figure 4b). The burnish and fracture height is much more homogeneous along hole perimeter for lab 2 in comparison to lab1 punched holes. For both cutting
tools the local clearance, which gives an indication of local punch to die alignment/coaxiality, is quite irregular and varies between 6 and 14% for lab 1 cutting tool and 5% to 15% for lab 2 cutting tool. Burr occurs occasionally with both punching tools. Previous investigations showed that there is no significant influence of the positioning of the blanks during punching and HET. Therefore, tests were conducted with varying orientation of the blank with respect to the punching tools as well as the HET tool.

![Figure 4](image_url)

**Figure 4.** Cut edge parameters from metallographic cross sections, punched hole at lab 1 vs. lab 2.

5.2. Cut edge parameter from microscope front view

Some additional punched holes have been investigated with an optical microscope in a front view modus after hole cutting in 4 parts (**Figure 5**a). Pictures have been taken around each 30° along cut hole (**Figure 5**b shows the estimated cut edge parameters (fracture, burnish and rollover in % normalized over 2.0mm thickness) versus angle to rolling direction from such front view in 30° steps along cut hole circumference for lab 1 vs. lab 2 cutting tools (2 replicates each). Strikingly the fracture and burnish parameters for punched holes at lab 2 are much more stable along hole diameter in comparison to lab 1 hole cut edge quality. The cut edge burnish and fracture height patterns are however not reproducible from test to test for lab 1 cutting tool with strong variations between one hole location to another. This confirms the previous results from metallographic sections in **Figure 4**.

5.3. HER round robin test: effect of cutting tool vs. hole expansion testing

**Figure 6** shows the hole expansion ratio values (average based on 10 replicates for each set of parameters). The minimum and maximum HER-values are plotted as error bars in the diagram together with the standard deviation of test results. The hole punching has been performed either at lab 1 or lab 2, the HET testing has been made in the same laboratory as soon as possible and after one month. Some punched samples have also been exchanged and tested after one month in the partner laboratory.

Hole expansion values based on lab 2 hole punching are significantly higher around 10% than for the samples punched at lab 1. The HER values for a given punched quality are around 5% higher when tested at lab 1 in comparison to lab 2, regardless of the punched edge quality. The methodology for the hole expansion test used at lab 1 delivers higher HER values, while the HER values are increased for the samples punched at lab 2. The scattering within each testing parameter set is non negligible.

Around 2/3 of the differences in HER values originate from punched edge quality, one third from the hole expansion testing itself. A five times larger drawing clearance between hole expansion punch and die is observed for lab 2 in comparison to lab 1 HET setup (**Table 1**). Stronger resulting bending
strain gradient may postpone necking occurrence with some benefits for HER values at lab 1 in comparison to lab 2 samples. Similar results have been also observed in [7]: the larger the gap between hole expansion punch and die, the lower the HER-values. No specific requirement is given however on hole expansion die diameter (> 40mm) according to ISO16630. Some Auto/Steel Partnership (AS/P) recommendations are made in [8] with a minimum of punch diameter around 40mm and a die diameter of 52±2mm, which delivers a 6mm punch to die clearance in order to be able to draw up to 6mm thick materials according to ISO16630 specifications.

Surprisingly, the effect of cutting clearance homogeneity along the hole perimeter is not the dominant parameter on HER. For both tools the local cutting clearance as seen in metallographic sections is not constant but varying from 5 to 15% locally. The homogeneity of fracture and burnish height along the hole circumference is rather the dominant parameter. Local irregularities in cutting parameters may cause some premature crack initiation. The delay between punching and HET testing seems to have no influence on HER values for this particular hot rolled steel.

Figure 5. Cut edge parameter from microscope front view along hole cut edge circumference.

Figure 6. Hole expansion values with same punching tools and different HET machines.
6. Conclusions
A very significant span between maximum and minimum hole expansion ratio values can be obtained within the ISO16630 standard for hole expansion ratio for the investigated high strength hot rolled steel. The punching tool setup account for around 2/3 of the differences in HER observed (10%). The performance and evaluation of the hole expansion testing itself plays also a smaller role accounting for 1/3 of the observed differences in HER (5%). Those differences cannot be attributed to cutting clearance or cutting tool wear, which have been documented to be quite comparable between both laboratories. The homogeneity of cut edge parameters in particular fracture and burnish height along hole circumference seems to govern the level of HER values. Each punching tool delivers a unique shear cut quality, which should be inspected and documented to assess the validity of HER values in any case. Immediate consequences of this study are that efforts to guarantee high quality punched edges are at least as important as efforts to improve the HER testing itself.

References
[1] Unruh K and Heuse M 2017 New challenges on materials evaluation for advanced high-strength steels in automotive seat structures. SCT Conf., June 18-22, Amsterdam, Netherlands.
[2] VDA 239-100 Material specification - Sheet Steel for Cold Forming, 05/2016.
[3] Lachmann C, Eberlein W, Lamprecht K, Tönnessen A, Dettinger T, Veith S, 2017 Global Standardization of Steel Sheet Products for Automotive Applications. SCT Conf., June 18-22, Amsterdam, Netherlands.
[4] Hance B M and Davenport M D 2016 AHSS: Deciphering Local and Global Formability. Int. Automotive Body Congress, Sept. 28-29, Dearborn, MI, USA.
[5] Larour P, Freudenthaler J and Weissböck T 2017 Reduction of cross section area at fracture in tensile test: measurement and applications for flat sheet steels. J. Phys. Conf. Ser. 896 012073.
[6] ISO 16630:2009 (E): Metallic materials-sheet and strip-hole expanding test.
[7] Larour P, Pauli H, Freudenthaler J, Lackner J, Leumann F, Schestak G 2016 Experimental artefacts on ISO 16630 hole expansion ratio. IDDRG 2016 Int. Conference, June 12-15, Linz, Austria.
[8] M. Huang and J. Singh 2014 Auto/Steel Partnership A/SP Standardization of Hole Expansion Test. Great Designs in Steel. May 14, Livonia, Mich., USA.
[9] Larour P, Freudenthaler J, Eßbichl R, Eßbichl R, Kerschbaum M, Horinek H, Samek L, Influence of shear cut edge condition on conical hole expansion ratio. SCT Conf., June 18-22, Amsterdam, Netherlands.
[10] Wang N and Golovashchenko S 2016 Effect of Tool Stiffness and Cutting Edge Condition on Quality and Stretchability of Sheared Edge of Aluminum Blanks. SAE Technical Paper 2016-01-0348.
[11] Stemler P, Samant A, Hofmann D, Altan T 2017 Impact of Servo Press Motion on Hole Flanging of High Strength Steels. SAE Technical Paper 2017-01-0311.
[12] Slavic J, Bolkça S, Bratusch V, Boltezar M, 2014 A novel laboratory blanking apparatus for the experimental identification of blanking parameters. Journal of Materials Processing Technology 214, pp 507-513.
[13] Jaafar H, Mori K, Abe Y, Nakanishi K, 2016 Automatic centring with moving die for cold small clearance punching of die-quenched steel sheets. Journal of Materials Processing Technology 227, pp 190-199.
[14] Ragu K 2014 Experimental analysis of die clearance distribution in a press tool assembly. Transactions of FAMENA, Vol. 38, No.4, pp. 55-64.
[15] Dayton Today’s Solutions Newsletter 2012 Taking Advantage of Proper Punch and Die Alignment. March 6, Vol. 2, No.3. http://www.daytonprogress.com/lists/archive/15.php
[16] Dayton Today’s Solutions Newsletter 2012 Effective Cures for Lateral Deflection in Perforating. May 15, Vol. 2, No.5. http://www.daytonprogress.com/lists/archive/17.php
[17] Siddhurth Upadhya, Staupendahl D, Heuse M and Tekkaya A E 2018 Improved Failure Prediction in Forming Simulations through Pre-Strain Mapping. ESAFORM Conf., April 23-25, Palermo, Italy.