Modelling stamped edges in FEM breakage analyses of high-strength steel safety components

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Abstract. The development process for new safety components includes break load tests, where the component undergoes very large strains. Besides the mechanical properties of the steel, which are changed by the forming process, the break load depends on the quality of the stamped edges. Target of this paper is to investigate whether a hole-tensile test with a stamped hole can demonstrate the effects of stamped-edge quality on the load bearing capacity – and secondary, how such a test procedure can be reproduced with a multi-scale FEM procedure. A series of Hole Tensile Tests (HTT) has been performed with a HSLA steel grade. Here, only minor differences in break load and total elongation were found. The local strain just prior to breakage at the edge of the stamped hole shows remarkably high values, but little difference is found when comparing a machined sample to stamped samples. The multi-scale FEM approach was demonstrated using literature data for dual-phase steel, which is known to be more sensitive to edge cracks. Indeed, a stamped edge, which includes significant hardening and pre-damage, shows earlier fracture in this FEM calculation – however, the crack propagation, which is needed to capture the full breakage of the HTT sample, is not modelled correctly – this limits the application of the method on safety components.

1. Introduction
The influence of the blanking or shear-cutting process on the failure behaviour of sheet metal material edges has been widely investigated for deep drawing operations and is also partially simulated with sufficient accuracy [1-5]. However, the influence of the stamping process on the breaking load behaviour of stamped safety-related components in belt systems is less frequently explored in literature. In a dynamic loading scenario, safety components may undergo very large deformations: Clearly, a premature initiation of failure at the stamped edge is unacceptable.

Figure 1 shows high tensile strain in the bent area (point A) of a simplified example bracket. Two distinct failure modi, also known from physical break load tests [6], have been reproduced in FEM by setting the limit strain $\Delta$local at a lower and higher value in the material model – failure at the bending (Figure 1 – centre) reduces the break load significantly [6]. The maximum bending strain at point A, is on a stamped edge of the bracket. Hence, it is natural to assume an influence of the stamped edge stretchability on the break mode and break load.
To achieve no-compromise quality for safety related components, both the material selection and the design of the shear-cutting process must be carefully assessed in the component design phase already. This requires that the edge properties resulting from material selection and process design are known/understood and added as an extension to the above presented FEM break load model.

1.1. Literature on stamped edge stretchability
A shear-cutting process typically uses a punch, die and blank holder. The cutting clearance, which is the gap between die and punch (in this work represented by the character Q and expressed as % of the steel thickness), as well as the sharpness of the tool (e.g., the radius of the punch edge) define the characteristics of the shear face and the characteristics of the shear-affected zone (SAZ) for the sheared material [4]. To investigate the influence of the shear-cutting parameters on edge characteristics and consequently on the failure behaviour of the stamped edges in forming related operations, various experimental tests have been developed, such as Hole-Expansion Test (HET) [ISO 16630], Diabolo-test [19] or Half-dome-test [1]. The tensile test with one-sided stamped edge [7] and Hole-Tensile-Test [8-11] allow free loading of the stamped edge (e.g. not involving tool contact and friction) and thus better represent the loading situation in a safety component break load test.

The common finding from experimental tests is that the deformation in the SAZ is the dominant factor in controlling failure during stamped edge stretching [4, 11]. The presence of voids and microcracks plays a secondary role according [4]. As a side remark: [11] points at the differences in residual stresses after drilling or stamping as a future research topic.

While shear face characteristics and characteristics of the shear-affected zone correlate to the stretchability of the edge, one cannot determine the stretchability of the edge directly from the morphology of the shear face. Furthermore, the different types of steels, especially of different AHSS families (Complex-phase, Ferritic-Bainitic, Dual-phase) have different sensitivities to parameters in the stamping process [2, 11]. [17] compares hole expansion ratios for DP780 steel from 6 different suppliers: The authors found some supplier’s steel to show significant differences in Hole-Expansion Ratio (HER) when shear-cut with various clearances, the samples of other suppliers proved insensitive. In contrast to DP steels, only few experimental studies can be found in literature for HSLA steel, which is often used for safety components in belt systems (e.g., see example in [6] for a seatbelt bracket: S550MC).

1.2. Edge stretchability in FEM simulations
FEM simulations may be the key technique to fundamentally understand the stamped edge stretchability of various steel families (and differences between different suppliers) and to assess component performance in industrial context. [8-10] combine the shear-cutting step and Hole-Expansion Test in a single FEM model. This requires enormous computational effort since the stamping process requires high-resolution modelling, which limits industrial application. Two more efficient modelling approaches to model stretchability of stamped edges are often found in literature: The first approach is...
used in the context of sheet metal forming. It applies an empirical edge strain limit with fixed values to edge elements, such as the “edge forming limit” [5] or the commercially available option in AutoForm, demonstrated by [12]. In industrial practice, this requires a large library of material and process combinations. It is not clear how to generalize such an edge crack criterion to be included in a break-load simulation chain as presented by [6], which uses solid elements. How to set an edge forming limit strain for point A in Figure 1, or the limit strain on the surface of a hole-tensile test?

The second (less empirical) approach maps accumulated damage and hardening from a high-resolution shear-cutting simulation (in-plane simulation) to the coarse mesh in the macro scale load scenario. This approach is called “multi-scale approach” throughout this paper and can be included into the sequential forming and break load simulation chain such as presented in [6].

FE simulations of the shear-cutting process can be found in various literature (for example [8-10, 12, 14, 15, 18]). The simulations are generally in good agreement with physical tests, specifically in terms of shear face characteristics and hardening distribution in the SAZ, even for simplified material models. The challenge is, to capture the stretchability of this edge in the secondary forming or break load (or dynamic loading) scenario, using the same material model. [8-10] and [18] report that the multiscale approach in HET give good results for HER, where edge failure (initiation of a crack) is defined by the deletion of first edge elements. This paper focuses on the multiscale approach in the context of safety component breakage tests, summarized in two research questions:

1. Can a hole tensile test, using HSLA steel, be used to assess a potential drop in break load on a stamped component with decreasing edge quality? How can the maximum strain at the stamped edge be measured in-situ?
2. Can the influence of shear-cutting be accurately covered by a sequential (multiscale) shear-cutting and break load simulation, using the simplified material model from [6]?

2. Experimental testing
This paper uses the HTT to show differences in break load and elongation from macro-viewpoint (over the sample as a whole), but also to measure the maximum local strain at the hole just prior to breakage, using digital image correlation (DIC). In this section, results from HTT experiments are reported, using a high quality HSLA steel and various cutting clearances on the stamped hole. Unlike the HET, the HTT shows friction-free loading of the stamped edges which matches the loading situation of safety components in break load tests well.

2.1. Material and sample geometry
The used material is an EN 10149 S700MC hot-rolled HSLA steel with sheet thickness 3 mm and following mechanical properties: Rm = 789 MPa, Rp0.2 = 735 MPa and A5 = 21.7 %. There is no generally accepted standard for the HTT: Various specimen geometries can be found in the literature (for example, [8] and [11]). The sample shape used in this work is shown in Figure 2. A hole is stamped in the centre of the specimen with a diameter of d0 = 10 mm, using a HET stamping toolset (i.e. the die diameter is varied to achieve different cutting clearances - this has been found to have just minor effect on the load-bearing cross-section and hence on the maximum load of the HTT and is therefore neglected in this work.). A cutting clearance. Q = 5.8% is representative for stamping of HSLA in serial production. It produces a large burnish zone but induces considerable cold work hardening in the SAZ. Q = 19 % leads to a smaller burnish zone and more microcracks but reduces the cold work hardening in the SAZ. Reference specimens (hole edge in initial material conditions) have been obtained from stamped hole HTT by milling the shear-affected zone (i.e. 500 µm on the circumference) away. The amount of 500 µm for the SAZ was determined from hardness measurements in the cross-section perpendicular to the punched edges. The hole for the milled HTT has consequently a larger diameter of 11 mm. The resulting reduced load bearing cross-section in the HTT due to the milling has been taken into account in the given results. The test program includes three samples each for Q = 5.8 %, Q = 19 % and for milled hole.
2.2. Break load testing and DIC measurement
During the HTT, strains are measured locally with a GOM ARAMIS® optical system. The resulting data files contain information about the deformation on the surface as well as the measured pulling force from the universal testing machine (UTM). The time of crack initiation is determined visually for all tested specimens (i.e., last picture frame before a visible crack occurs). Figure 3 shows exemplarily contour plots (technical strains) for an HTT sample with \( Q = 19\% \) in three different deformation stages (i.e., early deformation stage in a); last frame before fracture is detected in b); visible fracture in c)).

![Figure 2. Specimen geometry for the Hole Tensile Test.](image)

![Figure 3. Exemplary Aramis results for HTT with \( Q = 19\% \): Contour plots of technical strains at three different deformation stages.](image)

2.3. Applied methodology for limit strain analysis
In the initial (undeformed) stage, an ellipse was fitted along the points of the inner boundary (i.e., the hole – see Figure 4 a) of the ARAMIS® generated mesh. Multiple parallel sections at a distance of 0.125 mm were generated, with the mid-section passing through the centre of the ellipse (see also Figure 4 a). On the 5 inner cross sections a total of 10 inspection points were set symmetrically on both sides of the hole at a distance of approximately 0.4 mm from the edge (see Figure 4 b). The technical strains are exported for all available stages. The maximum strains from the 10 inspection points of the left and right side are taken at the last picture frame before a visible crack occurs to represent failure of the specimen (see Figure 4 c).

![Figure 4. Schematic representation of the applied methodology for strain analysis procedure for HTT.](image)
2.4. Experimental Results

The results of the strain analysis described above for all HTT tested in this work are given in Figure 5 in terms of technical strains in loading direction of the specimen. A box plot format is used to capture the statistic characteristic of the determined fracture strains (note: 20 strain data points are evaluated for each single specimen). The results in Figure 5 shows that there is no significant difference on the average technical strains at fracture for the two tested cutting clearances (i.e., $Q = 5.8\%$ and $Q = 19\%$). Furthermore, it can be seen from Figure 5 that the strain values for HTTs with $Q = 19\%$ show higher variances. For the milled specimens, a trend towards higher average technical strains in the critical regions seems to be present.

![Figure 5](image)

**Figure 5.** Results of fracture strain evaluation for the HTT specimen with cutting clearance of $Q = 5.8\%$ and $Q = 19\%$. 20 strain data points are evaluated for each single specimen and are given in a box plot format for each specimen to capture the statistic characteristic of the determined fracture strains. The results for HTT with milled hole are given as a reference.

The synchronized force signal from the ARAMIS® result file was exported for all available stages and related to initial critical cross-section to account for the different hole diameters for stamped and milled hole. For the displacements, two-point distance at the stamped hole in loading direction (see Figure 4 a) – marked with white arrow) was used. Figure 6 shows results in terms of engineering stress over a relative measure for displacement (i.e. relative Y distance).
Figure 6. Engineering stress over corrected relative distance Y for the tested HTT specimen. The point of fracture initiation is marked for all specimens. (Note: The corrected relative distance Y on the abscissa is based on the elongation of the punched hole in loading direction and was chosen to account for different initial diameters d0.)

From Figure 6 can be seen that stamped as well as milled HTT specimens show very good reproducibility. There are no significant differences between the achieved maximum engineering stresses for stamped and milled holes in HTT. Between Q = 5.8 % and Q = 19 % specimens a slight difference in maximum stress can be observed. This is probably due to a differently pronounced shear-affected zone as well as the load-bearing cross sections due to the change in cutting clearance. Regarding the maximum displacements before visible cracks occur (marked with circles for stamped holes in Figure 5) there is no significant difference between the specimens with cutting clearances 5.8 % and 19 % that could be attributed to differences in the shear-affected zones. The maximum displacements for the milled specimens (see triangles in Figure 6) exceed those seen in the specimens with stamped holes.

3. Multiscale FEM modelling of HTT with stamped edge
This section describes an investigation into a FEM multiscale approach for the hole tensile test, with stamped edges. The study uses HTT data for DP780 steel with 1.6 mm sheet thickness, taken from literature [8]. This basis for the data has been chosen, and not the produced results from the presented HSLA test campaign, because neither the force-displacement (Figure 6), nor the DIC strain measurement (Figure 5) tests showed a clear dependency on the edge properties (milled, stamped, clearance).

3.1. Model description and material modelling
Figure 7 a and 7 b show the dimensions and meshing details of the LS-DYNA FEM simulation model (half-model) for the HTT according to [8]. In the HTT FEM model, solid elements with element size 0.1 mm are used. The meshing directly at the edge of the hole in the HTT model is obtained with 5 element ring layers which allow to represent the so-called shear-affected zone of a stamped edge (see Figure 7 b).

A simplified material model for plasticity and fracture has been derived from the DP780 mechanical properties in [8] and [10]. The methodology used generates an elastic-plastic FEM material model including breakage from tensile test values (e.g. a material certificate) alone. In this method, there is no accumulation of damage in the form of stiffness degradation – when the limit strain (in dependency of the triaxiality) is reached, failure is instantaneous, and the element is deleted. The details on the methodology are given in [6]. The validation of the simplified plasticity and fracture model for the DP780 shows good correlation with the reported experimental values in [8]: Slightly higher force values
are obtained in the force/displacement results which may be attributed to the isotropic plasticity in the material model. The maximum displacement at failure from the FEM HTT simulation with the simplified material model falls well into the range of the experimental results given in Figure 14b in [8].

3.2. Multiscale approach – mapping 2D cutting simulation results onto 3D model
In [10] detailed axis-symmetric 2D cutting simulations have been conducted for the investigated DP780 grade for various cutting clearances. The pre-damage and plastic strain values obtained from 2D cutting simulations for different cutting clearances show relatively small variations compared with the overall pre-damage. Also, pre-damage and effective plastic strain have a nearly identical distribution and can be scaled by a factor into each other [10]. Fundamentally, it may make sense to analyse pre-damage and cold work hardening individually (and pre-damage as a tensorial parameter [20]), however, this does not match with the simplistic material model [6] and should be focus of future work.

![Figure 8. Initial conditions of the hole tensile test FEM model – mapping of pre-strain values onto the 3D model (no pre-strain for “milled” hole; max. value; 50% mean/max. values; mean value).](image)

For demonstration reasons, an average pre-damage continuous distribution is obtained for all die clearances in [10] (the reader is referenced to Figure 19 in [10] – this distribution serves as the master curve representing a shear-affected zone. Superimposing this curve on the element discretization at the edge in the 3D model (the 5 rings), the question arises as to which discrete curve values should be transferred to the integration points of the individual elements of each ring as the initial condition. In this work, the mean values, the maximum values, and values in between the aforementioned values (50% mean/max. values) from the master curve have been explored in the multiscale FEM concept (see Figure 7 c for the three different effective plastic strain distribution that serve as initial condition in the FEM model to represent the SAZ). Figure 8 shows the HTT FEM model with the different pre-strain distribution as initial condition in the SAZ.

3.3. Simulation results
Figure 9 shows the numerical force/displacement results for the HTT were pre-damage and pre-strain values have been considered at the holes edge as described above. The force-displacement results from the HTT simulation model representing edge conditions for milled edges (i.e. no shear-affected zone) is given as a reference (i.e. grey solid curve in Figure 9). The results show that earlier fracture occur in the HTT FEM models where stamped edges are considered. The numerically predicted total elongation of the sample lie clearly above the experimental range for stamped edges (i.e. light-grey marked area in Figure 9 - the reader is referred to Figure 14b in [8] for the detailed experimental results). Furthermore, it can be seen from Figure 9 that there is no significant difference in the force/displacement result for the three different degrees of the pre-damage/pre-strain at the holes edge (i.e. the black solid curve, grey dotted curve and grey dashed curve in Figure 9 to represent different degrees of pre-damage).
A more detailed look on the failure evolution in the FEM model where stamped edges have been considered via initial pre-damage and pre-strain values shows that for the highest pre-damage degree (grey dashed curve in Figure 9 (left), and the grey dashed column (right)) a first through thickness element deletion happens already in the very beginning of the component stretching. In the force/displacement curve this event is visible through very small kink in the curve (indicated in Figure 9 with the grey dashed arrow). The further evolution of the force/displacement curve after first through thickness element deletion follows qualitatively the force/displacement behaviour of the “pre-damage mean value” model (i.e. black solid curve) but a slightly lower force level. The slightly lower force level can be attributed to the reduced cross-section at the critical area through element deletion. For the grey dotted and black solid curve similar behaviour is observed in terms of element deletion but at later simulation stages. However, it becomes clear from this results that a first through thickness element deletion with element size of 0.1 mm does not trigger macro scale fracture in the HTT model making the overall force/displacement answer independent of the edges pre-damage values for the investigated pre-damage degrees.

4. Discussion

Can a hole tensile test, using HSLA steel, be used to assess a potential drop in break load on a stamped component with decreasing edge quality?

Firstly, in the maximum values of engineering stress in the engineering stress/displacement curves (Figure 6) of the hole-tensile-tests for the S700MC (HSLA) samples, no clear distinction can be made between milled and stamped specimens, and obviously, no difference can be observed between the two cutting clearances either. More interestingly, the overall elongation-before-breakage of the samples has only a minor advantage for the milled sample. This insensitivity of the HSLA samples is in sharp contrast to the published curves for DP780 by [8]. Secondly, the mean value of the measured (eps yy technical) strains are, for all samples, well above 100%. Whereas HSLA steel is known for superior local ductility, the authors interpret the measurement values as proof of an exceptionally “damage tolerant” steel. The strain at breakage is higher for the milled samples, hinting at an influence of the stamped edge, but not significantly so.

Hence, for the measured batch of steel, the HTT is unable to link stamped edge quality to macro-level breakage. The authors recommend analysis for a series of HSLA steels from various suppliers, similar to [17] to learn whether the insensitivity of HSLA in an HTT is fundamental.
Looking back at the example bracket in Figure 1, the HTT procedure lacks the typical strain reversal of the safety part application [6], where a flat, stamped blank is bent into shape as a bracket which is then pulled flat again in a subsequent load scenario: The test procedure should include shear-cutting, forming and then the break load situation as a third step. Future analyses could extend the stamp+bend test in [16] with a subsequent tensile stage.

Can the influence of shear-cutting be accurately covered by a sequential (multiscale) shear-cutting and break load simulation, using the simplified material model from [6]?

Because of the insignificant differences in the experimental HTT results for HSLA, the originally intended combination of physical tests and FEM analysis was not followed up in this paper. When published [8] DP780 plastic strain and pre-damage in the SAZ are mapped onto the mesh of an HTT sample, the early onset of a crack is indeed reproduced in FEM. However, the crack initiates at the wrong time, and the propagation is captured incorrectly. This is easily understood as the used [6] material model does not include crack propagation physics: element deletion is instantaneous once the strain limit is reached. Also, the element-wise deletion is likely to be much too coarse to capture the crack propagation.

To assess the break load of safety components with stamped edges, crack propagation is likely the key aspect. Basically, any stamped edges will have some level of microcracks: The main question is whether these propagate into a macro breakage or not.

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