Experiments and FE-simulations of stretch flanging of DP-steels with different shear cut edge quality

M. Sigvant\textsuperscript{1,2}, J. Falk\textsuperscript{1} and J. Pilthammar\textsuperscript{1,2}

\textsuperscript{1} Blekinge Institute of Technology, Valhallavägen, 371 41 Karlskrona, Sweden
\textsuperscript{2} Volvo Cars, Dept 81153 Stamping CAE & Die Development, 293 80 Olofström, Sweden

Corresponding author: mats.sigvant@volvocars.com

Abstract. Dual-Phase (DP) steels are today used in the automotive industry due to its large strength to weight ratio. However, the high strength of DP-steel does have a negative impact on the general formability in sheet metal forming. Unfavourable process conditions in the press shop will, on top of this, reduce the formability of DP-steels even more. This paper addresses the problem of edge fracture in stretch flanges in sheet metal parts made of DP-steel. The experimental part involves tests of ten different DP590 and DP780 steel grades with three different shear cut qualities. The influence on the fracture strain of the sample orientation of the shear cut are also studied by facing the burr away or towards the punch and testing samples with the cut edge parallel with the rolling direction and the transverse direction. The strains are measured with an ARAMIS system in each test, together with punch displacement and punch force. All tests are then simulated with AutoForm\textsuperscript{\textregistered} plus R7 and the results from these simulations are compared with the experimental results in order to find the appropriate failure strain for each combination of supplier, coating, thickness and shear cut quality.

1. Introduction

Volvo Cars as well as many other companies in the automotive industry uses Dual-Phase (DP) steel in their car bodies due to its high strength to weight ratio. This property of the material makes it ideal for weight reduction and to increase strength of body parts like beams, cross members and pillars. However, the formability of these grades are limited and unfavorable manufacturing process conditions in the press shop will, on top of this, reduce the formability of DP-steels even more. Shear cutting of DP-steels is an example of a manufacturing process that can reduce the formability of DP-steels. In general, DP-steels requires different settings compared to die shear cutting of a conventional low-carbon steel and these conditions will then change during production due to wear of the shear cut die. Finally, there will be an edge fracture in the stretch flange if the wear will go on too long without any stamping die maintenance, see figure 1.

There are at least three major problems connected to shear cut edge fractures. Firstly, these fractures are normally quite small and hard to detect by the staff in the press line. Since these parts are important parts of the cars safety cage, a missed edge fracture could have a negative influence in different crash situations. Secondly, these fractures tend to occur at a very late stage of the manufacturing of a stamping die or even after the start of the production, which generally makes it hard to change the part design in order to solve the problem. The late occurrence of the fractures is due to the fact that at an early stage of die manufacturing, the trimming of the part is made by laser which results in a high quality edge with
no problems of fractures. It is therefore favorable to evaluate the risk of edge fractures in the sheet metal forming simulations and then try to eliminate them during the die design phase. But this leads to the final major challenge with this type of fractures, which is how to define suitable failure strain limits for different shear cut conditions for evaluation of the risk of edge fracture in the sheet metal forming simulations.

This paper presents some of the results from [1]. The purpose of the current study is first to develop a test set-up, that results in different failure strains for different shear cut qualities and then to determine appropriate failure strains for each shear cut quality that can be used in sheet metal forming simulations.

Finally, a short note regarding the use of the terms fracture and failure when describing the limiting strain in this paper. At first, one could conclude that these terms are identical but a closer examination reveals an important difference and in this paper the following definition is used. The fracture strain is the maximum strain measured in an experiment before a fracture starts, e.g. in the Concentrated Trim Edge Strain Test (CTEST) or in an FLC-test. The failure strain is the strain when the part is no longer fulfils the requirements, e.g. onset of necking, or the limit strain in an FE-simulation that predicts onset of edge fracture at the same punch depth as in the corresponding experiment. This difference is important to keep in mind when results are discussed and shared.

2. Method

2.1. The Concentrated Trim Edge Strain Test (CTEST) method

The CTEST method used in this study is based on ideas, presented in resent research papers, combined with the authors own experience from material testing. The punch design is of Diabolo-type and is inspired by [2] and [3] but further developed by Volvo Cars within this study. The idea of using ARAMIS for the strain measurements in edge fracture tests is proposed by [4]. The set-up with one polished or milled edge and one shear cut edge on the test samples was presented in [5]. The authors major contribution to the CTEST method is to determine the failure strain by inverse modelling.

2.2. Material grades used in the study

In this study, ten different DP590 and DP780 grades, used in Volvo Cars production today, were tested. All samples are delivered to Volvo Cars according to the VDA239 specification [8]. The difference between the different grades were sheet thickness, surface coating and material supplier, see table 1 for details.

2.3. Experimental set-up

The experiments are performed with a single action stamping die that is used for different types of material tests, e.g. FLC-test and LDH-tests, at Swerea-IVF in Olofström, Sweden. During the each test the test sample is locked by a draw bead. The sample dimensions are 50x190 mm and the samples are
manufactured in an experimental shear cut die where the trim steel can be changed and moved so that the desired combination of trim steel radius and cutting clearance can be achieved. All samples have one edge that is polished and one edge with varying shear cut quality. The purpose of this set-up is to force the fracture to the same edge in all tests. Teflon foil and lubrication are added in all tests in order to reduce the friction so that the maximum strain occurs in the center of each sample. During each test the strains in the sample, the punch displacement and the punch force are recorded with a 60Hz ARAMIS 4M system from GOM. The major strain, predicted by AutoForm in one test together with the punch geometry is displayed in figure 2.

Table 1. Materials used in the study.

| Grade | Coating | Thickness | Supplier |
|-------|---------|-----------|----------|
| 1     | DP590   | GI        | 1.0      | A        |
| 2     | DP590   | GI        | 1.0      | B        |
| 3     | DP590   | GI        | 1.0      | C        |
| 4     | DP590   | UC        | 1.1      | A        |
| 5     | DP590   | GI        | 1.5      | A        |
| 6     | DP590   | GI        | 1.5      | B        |
| 7     | DP590   | GI        | 1.5      | C        |
| 8     | DP590   | GI        | 2.0      | A        |
| 9     | DP780   | GI        | 1.0      | B        |
| 10    | DP780   | GI        | 1.5      | B        |

Figure 2. Major strain predicted by AutoForm plus R7. The used punch geometry is also displayed.

The experimental study was conducted in two series. The purpose of the first test serie was to decide on the experimental set-up by evaluating a large number of tests of Material 5 in table 1. These tests included different trim steel radii, trim steel clearances, samples with shear cut edges parallel with rolling direction and the transverse direction and finally with the burr facing upwards or downwards. In the first test serie, all tests were repeated three times. In the second serie, the remaining steel grades in table 1 were tested according to the set-up decided after the first serie. Each type of test in the second serie was repeated twice and if the scatter in punch depth at fracture is large, a third test was also performed.

2.4. FE-simulations
All tested cases have been simulated with AutoForm plus R7. The maximum punch displacement for each case was determined by the ARAMIS results, see Section 2.3. The material data for each grade is Volvo Cars standard data, that is normally used in car projects. The failure limits for each material in table 1 and shear cut quality are determined iteratively. First, a simulation is performed for each shear cut
quality with maximum punch depth from corresponding experiment and the Edge Crack value in AutoForm is evaluated. If this value deviates from 1, the limit value for the tested shear cut quality is modified and this procedure is then repeated until the Edge Crack value is 1 for each shear cut quality.

3. Results

3.1. Influence of trim steel radii and cutting clearance

The trim steel used for cutting the samples had two radii that could be used for shear cutting, one with 20 $\mu$m radius and one with 120 $\mu$m radius. In order to determine the three most appropriate settings for the rest of the study, four different combinations of trim steel radius and cutting clearance were tested together with a sample where both edges were polished. The results are presented in figure 3. Maximum punch depth in all figures in this paper is the lowest value of each combination and is determined at maximum punch force. The cutting clearance is stated in relation to the nominal sheet thickness.

![Figure 3. Maximum Punch Depth for different trim steel radii and cutting clearances.](image)

Figure 3 shows, that the combination of a trim steel radius of 120 $\mu$m and a cutting clearance of 20 %, results in the lowest punch depth at maximum force. This combination is therefore used for the conditions labeled Worn in this study. A smaller trim steel radius of 20 $\mu$m with a 20 % cutting clearance increases the max punch depth at maximum force and these settings are labeled Medium in this study. With a cutting clearance of 5 %, the maximum punch depth at maximum punch force is almost independent of trim steel radii. Furthermore, the punch depth at maximum force for these combinations are almost the same as the results for a sample with two polished edges. It was then decided that the conditions labeled Fine in this study uses a 120 $\mu$m trim steel radius and 5 % cutting clearance in order mimic the die wear that are present in the press shop after the die has been in production for a while.

3.2. Influence of rolling direction and burr orientation

Samples of Material 5 in table 1 were manufactured with shear cut edges parallel with the rolling direction as well as edges parallel with the transverse direction. These samples were then tested with the burr facing upwards away from the punch as well as with the burr facing downward towards the punch. The set-up with the burr facing upwards resembles the situation that the trimming and flanging is done in the same direction in the forming process, e.g. both operations are performed downwards. The other set-up, i.e. burr downwards, mimics the situation that trimming is done in one direction and the flanging is done in the opposite direction in the forming operation, e.g. trimming is done downwards and the flanging is done upwards.

Figure 4 displays the results of these tests. The Worn and Medium shear cut edge conditions and samples with shear cut edges parallel with transverse direction have similar maximum punch depths...
independent of the burr orientation. With the same shear cut edge conditions, but with samples with shear cut edges parallel with rolling direction, the burr orientation has got an influence. The maximum punch depth is larger when the burr is facing downwards compared to when the burr is facing upwards. Furthermore, the maximum punch depth values for samples with shear cut edges parallel with rolling direction and burr facing upwards are similar for samples with shear cut edges parallel with transverse direction independent of burr orientation. The results for Fine shear cut edge conditions are deviating from the other two shear cut conditions. The lowest maximum punch depth is with a shear cut edge parallel with the transverse direction and the burr facing upwards, the largest maximum punch depth is when the shear cut edge is parallel with the rolling direction and the burr facing upwards.

**Figure 4.** Maximum punch depth as a function of testing direction, burr orientation and shear cut quality.

For the remaining part of the experimental study it was decided to run all tests with the burr facing upwards. The motivation for this is that this is the most conservative setting according to results presented in figure 4, at least for Worn and Medium settings. The choice of using shear cut edges parallel with the rolling direction or the transverse direction is less obvious. In this study it was decided to use sample with the shear cut edges parallel with the rolling direction since that direction in combination with the burr facing upwards has low values in figure 4 for Worn and Medium shear cut conditions.

### 3.3. Maximum punch depth for all tested materials

Figure 5 presents the maximum punch depth for all materials in the study. For all tested materials, except Materials 1-3 and 9, the order between the different shear cut conditions are as in figure 3, i.e. Worn conditions result in the lowest maximum punch depth, Fine conditions result in the largest maximum punch depth and finally, Medium conditions result in a maximum punch depth between Worn and Fine conditions. The other materials, i.e. 1-3 and 9, have two things in common, they are all 1.0 mm thick and have a GI coating. For these samples, the Worn conditions still result in the lowest maximum punch depth values but the Medium conditions result in the largest maximum punch depth. The Fine conditions for these samples result in a maximum punch depth that is smaller, or for Material 3, similar to Medium conditions. The results for 1.0 mm thick GI material are hard to explain, but one conclusion drawn is that conditions that produce expected results for a 1.5 or 2.0 mm thick material don’t seem to be optimal for a 1.0 mm thick material. This makes the testing of edge crack problems even more complicated and challenging if different settings are needed for different thicknesses.

The uncoated 1.1 mm thick Material 4 has got higher maximum punch depths for Worn and Fine conditions than the Material 1, which is a 1.0 mm thick GI coated material from the same supplier. The explanation for this is that uncoated DP-steels are less sensitive for edge cracks than GI-coated grades due to a different manufacturing process at the steel mill. For the Medium conditions, the situation is reversed, i.e. the GI coated sample has a higher maximum punch depth.
3.4. Determination of maximum failure strain

The variation of maximum punch depth presented above is due to a variation of the fracture strain for each tested material and shear cut quality and it can be determined from the ARAMIS measurement. However, one purpose with this study is to determine the failure strain that should be used in AutoForm simulations of car body parts and it must be determined by inverse FE-modelling. If inverse modelling is used, the accuracy of strain distribution prediction from FE-simulations must be determined first.

Figure 6 displays the difference in major strain between the ARAMIS measurement and predicted strains by AutoForm\textsuperscript{plus} R7. The plot is created at maximum punch depth for Material 5 with Medium shear cut quality. A positive value in this plot indicates that FE-simulation is underpredicting the major strain and a negative values indicates that the FE-simulation overpredicts the major strain.

Figure 6 shows, that the FE-simulation predicts the major strain with a high accuracy in almost the entire sample, except for small area in the shear cut edge where the FE-simulation underpredicts the major strain. In this case, the maximum difference in major strain between measurements and FE-simulations is 0.13 which is quite large. The explanation for this difference is, that the shear cut edge has a number of fracture initiators that result in a strain concentration. A closer study of the images in the ARAMIS measurement reveals that there are several very small cracks along the shear cut edge and the one in the area with the large difference in major strain will start to develop a fracture across the sample in the next stages. The sheet mesh in FE-simulation doesn’t have any crack initiators and the...
FE-major strain will therefore be lower than experiments in this area. A similar result is also found for Worn shear cut conditions while the Fine conditions don’t have this strain localisation.

The result presented in Figure 6 stresses a very important point on how to determine failure strains that should be used in the FE-simulations. The fracture strain for the case in figure 6 is 0.43 and one could argue that this is also the failure strain that should be used in the FE-simulations. However, using the fracture strain as failure strain would lead to that the FE-simulation would indicate fracture at a much larger punch depth than in the corresponding experiment. Instead, it’s recommended to use the failure strain that results in an Edge Crack value of 1 at this punch depth and shear cut quality, which in this case is 0.28.

3.5. Failure strains for all materials from Supplier A
The materials in table 1 from Supplier A includes three different thicknesses of GI coated materials as well as an uncoated material. It is interesting to both compare all the determined failure limit values for these samples as well as comparing these values with necking and fracture limits from a FLC-test of a DP590 material from the same supplier. Figure 7 shows the failure strains determined with the presented CTEST-method for all Supplier A samples and shear cut qualities as boxes together with necking and fracture strains from an FLC-test of 1.5 mm DP590 GI coated material from the same supplier as lines.

![Figure 7. Failure strains from CTEST (boxes) together with necking and fracture strains (lines) for DP590 grades from Supplier A.](image)

The results show that unfavorable shear cut conditions will reduce the formability of the material tremendously. The strain path in the shear cut edge is close uniaxial and therefore should all the CTEST-values be close to the uniaxial fracture value if the shear cut quality doesn’t influence the formability. According to figure 7, this is only true for 1.5 and 2.0 mm thick samples and Fine shear cut conditions. For Worn shear cut conditions, the failure strains are lower than the uniaxial necking limit for all thicknesses. For the 1.0 mm thick GI sample and Worn conditions, the failure strain is less than 50 % of the uniaxial necking limit, which is a very low value. For Medium shear cut conditions, the failure strain is between the uniaxial necking and fracture limit for all thicknesses.

4. Conclusions and Discussion
This paper presents some interesting results on the topic of edge cracks in DP-steels. One conclusion is that it is possible to influence the fracture strain of a stretch flanged DP-steel with the shear cut edge quality in experiments. The problem with edge cracks is well-known from car body part production but when this study started, the authors were far from certain that it was possible to replicate the problem in experiments.

The proposed CTEST-method has got a few advantages over other methods proposed previously. The major advantage is that the failure limit strain is determined by inverse modelling, i.e. the failure
strain is determined by FE-simulation of the real experiment in each case rather than analysing the experiment itself. The presented results in the paper show that the shear cut edge has got a strain localisation with increased strain values along the edge just before fracture initiation. These localisations are not present in the FE-simulation since the samples edges are perfect in the FE-model which yields a lower shear edge strain in the FE-simulation than in the experiment. Therefore, using the fracture strain from the experiment will overestimate the materials formability and increase the risk for unreliable predictions of the risk of edge cracks. Another advantage with CTEST-method is the possibility to use advanced strain measurement systems, e.g. ARAMIS, in the experiments which is hard to use in a Hole Expansion test with vertical flanges. It is also possible to test the influence of the burr orientation which is not possible if the experiments are performed with a tensile test machine.

There are scatter in punch depth at maximum punch force in some of the cases. A large scatter of failure strain is also observed in other studies of edge cracks of stretched flanges and this will then result in a scatter of the punch depth at maximum force. To some extent this can be explained by the fact that fracture of the sheet material is studied, which in its nature is more stochastic than for example onset of necking. A larger scatter could therefore be expected, especially for shear edges with Worn or Medium settings. However, the results from this study cannot verify that only some types of shear cut setting have large scatter in punch depth at maximum punch force. There are numbers of test with Worn and Medium conditions that have very low scatter and also tests with Fine conditions that have large scatter.

5. Future Research
Future research should first focus on the shear cut setting for thin sheets. The results for 1.0 mm thick GI samples in this study indicate, that the shear cut conditions for these materials are not optimal for the purpose of this study. First of all, the failure strain is very low, even lower than the onset of necking at plane strain. Secondly, Medium shear cut conditions result in larger failure strains than Fine conditions. It seems that the choice of cutting clearance and trim steel radius that works well for 1.5 and 2.0 mm thick material is not optimal for 1.0 mm thick material. New combinations of clearance and radius must therefore be determined that is appropriate for 1.0 mm thick material, or the shear cut settings be should be modified for all shear cut qualities so that the same settings yields reliable results for all thicknesses. Also the influence on the failure strain values from the scatter in punch depth at max force should be determined.

This study focused on shear cutting of edges. It is also interesting to study hole piercing to see if this type of material shearing is also influencing the formability of the material. Also other type of sheet materials, e.g. different aluminum alloys, are interesting to test with the CTEST-method.

References
[1] Falk J, 2017, Fracture prediction of stretched shear cut edges in sheets made of Dual-Phase steel, Master Thesis at Blekinge Institute of Technology, (Karlskrona, Sweden).
[2] Wiegand K, 2016, Existing possibilities to predict edge cracks in the sheet metal forming simulation, Proc. of IDDRG 2016 (Graz, Austria).
[3] Liewald M and Gall M, 2013, Experimental investigation of the influence of shear cutting parameters on the edge crack sensitivity of dual phase steels. Proc. of IDDRG 2013, (Zürich, Switzerland).
[4] Atzema E and Seda P, 2015, Sheared edge tensile test improved: SETi, Proc. of FTF 2015 (Zürich, Switzerland).
[5] Volk W, Böttcher O, Feistle M, Gaber C and Jocham D, 2015, Advanced failure prediction in sheet metal forming, Proc. of FTF 2015 (Zürich, Switzerland).
[6] Teng Z K and Chen Z M, 2014, Edge cracking mechanism in two DP advances high strength steels, Materials Science & Engineering, (Michigan, USA).
[7] Zhuang X et al, 2014, Failure mode and ductility of dual phase steel with edge crack, Proc. of 11th Int. Conf. on Technology of Plasticity, (Nagoya, Japan).
[8] VDA239-100, 2016, Sheet Steel for Cold Forming, VDA-standard, (Berlin, Germany).