A new specimen for investigating shear fracture strain

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Abstract. In the automotive industry, the edge formability of a sheet metal part is usually defined by the Forming Limit Diagram despite its shortcomings. The success of the FLD can be explained by its easy applicability for dedicated FEM codes and physical measurements. However, the diagram covers a large range of strain paths of sheet metal parts, it does not fully specify the edge formability in the negative minor strain field, which is important for drawing operation with a small radius. This explains the great attention paid in the recent decade to the development of the shear test. Manufacturing the latest shear specimens (such as Butterfly or Smiley) is a significant cost and time-consuming process. In this paper, the applicability of a new flat shear specimen geometry was investigated, using finite element methods and physical measurements. Since the cracking can initiate on the boundary section of the flat specimen, first the effect of three different manufacturing methods (Wire EDM, laser cutting and drilling) were investigated. Based on the results a new flat specimen was created and optimized by finite element methods. The shear fracture strain of the new specimen was measured by an optical measurement system and the results were compared with the fracture strain of the smiley specimen.

1. Introduction

The Forming Limit Diagram (FLD) – originally presented by Keeler [1] and Goodwin [2] – is widely used in the automotive industry. The success of the FLD can be explained by the fact that it can be determined with a simple test [3][4], and can also be easily interpreted and applied in dedicated FEM codes. Despite the benefits, one of the biggest shortcomings of the FLD is the lack of fracture prediction in the field of negative minor strains. This shear type failure may occur in press shops in case of deep drawing operations which are performed by small radius tools [5]. An example specimen, whose tool geometry was inspired by the cross die of Frieder N. et al. [6] can be seen in figure 1. As it can be observed, a huge negative minor strain occurred, which does not cross the FLC, although, in the physical space, a shear fracture would probably occur. The presented case illustrated the reason the negative minor strain came forth, and the shear fracture strain became an important research area.

Nowadays there are several methods to determine shear fracture strains. These methods operate with parallel translational displacement, to deform a shear zone [7]. The most common method is to use a tensile loaded shear specimen based on ASTM B831 [8]. Due to the shortcomings of this method (for example rotation of gage section [7]) new different methods have become widespread like the plane torsion suggested by Marciniak [9], or after the work of Maysam Gorji et al.[10] the experimental cup drawing test based determination. However, the most common way to determine shear fracture strain nowadays is to still use the tensile loaded shear specimen with reduced gage section thickness [11].
Thin sheets with high strength are becoming more common [12], due to compliance with environmental regulations. However, manufacturing the so-called Butterfly, or other specimen based on this principle [13] can be difficult for thin sheets, therefore flat specimens are also being developed. To prevent the rotation of the sheared zone double gage section is used, for the so-called smiley specimen [14]. A common problem with these specimens is that the initiation of a crack is more likely under tension stress state at the free specimen boundary, rather than under pure shear. Mohr et al. [15] improved the smiley specimen based on an iteration-simulation method and based on the results of their simulations the location of the crack was already appropriate. However, the new specimen geometry varies as the properties of the material.

![Figure 1. Strain distribution a.) of a small radius draw part b.)](image)

In the case of flat specimens, the effect of manufacturing also plays an important role in preventing the boundary crack initiation. In this paper, the effect of three different manufacturing technologies was examined. Taking into account the results, and the problems with the flat specimens mentioned so far, the purpose of this article was to design a new, easy-to-manufacture geometry for a tensile loaded shear specimen. Investigation and optimization of the possible geometries were done by FE modelling. The tests were performed on DP800 steels with a thickness of 1 mm.

### 2. Effect of manufacturing

Early initiation of cracking from the boundary can lead to false determination of shear fracture strain. To investigate this phenomenon, the effect of different manufacturing technologies on the measured shear fracture strain was studied. The smiley specimen (modified specially for DP800 by Mohr et al.) was manufactured with laser and wire EDM cutting methods, and the strain to fracture was measured with the GOM system. In the case of the wire EDM specimen, the measured shear fracture strain was 0.85 (which can be compared with the work of Mohr et al.), while, with the laser-cut specimen the shear fracture strain has a much lower value, 0.57.

To better understand this phenomenon, the boundary areas for both technologies were compared based on microstructure and hardness. The results of the tests can be seen in figure 2. There were no significant changes near the cutting surface, neither in the microstructure nor in the hardness for the wire EDM specimen. The hardness of the laser-cut specimen increased significantly towards the cut surface. The change in the hardness can be explained with the approximately 30 µm fine-grained and recrystallized layer (this can also be observed in the figure) which is the result of the rapid heat dissipation during the cutting.
Since the main purpose of the paper was to design an easy and quick to manufacture tensile loaded shear specimen, the effect of milling was also investigated. As can be seen in figure 2, some increase in hardness is observed near the milled surface. The near-surface microstructure undergoes plastic deformation by the chip removal, so the increase of the hardness can be explained by the deformation hardening behaviour of the material.

![Figure 2. Hardness distribution and microstructure of cut surfaces](image)

Comparing the analyzed technologies, the best results in terms of microstructure and mechanical properties can be obtained with the most complicated and time-consuming wire EDM. The worst result was achieved with the time-efficient laser cutting. Since the main purpose of the paper is to design a simply manufacturable shear specimen that is accessible to everyone, the milling was selected the future work.

3. Development and FE investigation of a new shear specimen

The main goal -taking into account the possibilities based on the results of the previous chapter- was to design a specimen, consisting of simple geometric components that can be manufactured by milling (or even drilling). The efficiency of the geometries was examined by DEFORM finite element modelling software, taking the deformation and stress state into account. The shear specimen was optimized for DP800 high strength steel.

3.1. Material properties and simulation boundaries

A standard tensile test has been carried out to determine the flow curve of the DP800 steel. The flow curve, derived from the results of the tensile test, was then extrapolated with the combined Swift-Hockett/Sherby approach:

\[
\sigma = (1 - \alpha)C\left(\varepsilon_{pl} + \varepsilon_0\right)^m + \alpha\left(\sigma_{sat} - \sigma_i\right)e^{a\varepsilon_{pl}}
\]

\(\sigma\) and \(\varepsilon\) are stress and strain, the used parameters were: \(C=1223\) MPa; \(\sigma_{sat}=1009\) MPa; \(\sigma_i=514.8\) MPa; \(\alpha=0.25\); \(m=0.102\); \(a=6.89\); \(p=0.489\). For the plastic behaviour of the material, Hill48 was used. The
mesh was built by an 8 node brick element, 4 elements in the thickness direction (with the average size of 0.2 mm in the gage section) were used. For the deformation upward velocity to the upper nodes and fixed boundary condition for the other side was defined.

3.2. Investigated geometries
The efficiency of a shear specimen is fundamentally determined by the geometry of the gage section, and the way the shear strain realized on it. Accordingly, the shape and dimension of the shear zone were designed based on two main aspects. First, the dimensions of the sheared zone need to be the same as the sheet thickness, the second, was to make the contour of the gage section to be manufactured by milling or drilling. During the design of the specimen, the mode of deformation of the gage section needs to be taken into account, the displacements required to be parallel, but the movements need to be in the opposite direction. It is also essential that the process remain constant until the fracture. To achieve all of these parameters, a specimen with a double gage section was designed. In this case, due to the properties and dimensions of the manufacturing method, the gage section was located parallel to the load axis. The concept of the specimen can be seen in figure 3.

The optimal geometry of the shear specimen depends on the properties of the material. To optimize the specimen for DP800 steel, the dimensions shown in figure 3 marked with a, b, and c, were changed to create the new specimens. First, the effect of different diameters (so the width of the gage section) was examined in the range from 2-5 mm. Second, the distance between the centers of the holes was changed in the range of 4-7 mm (adjust thereby the length of the section). Third, the effect of the angle between the shear zone and the load axis was examined (from 0 to 90 clockwise). Only one of the above-mentioned parameters was changed at the time, to observe its effect, all the others remained constant.

![Figure 3. Concept of the specimen](image)

3.3. Results of FE investigation
The suitability of the newly designed test specimen was determined based on the strain path to fracture, the stress triaxiality (η) and the Lode angle parameter (ξ). In the former, the correct direction and straightness of the path were taken into account, in the latter, the value as a function of the strain was studied. The value of the latter was calculated -assumed plane strain condition- as follows [16]:

\[ \eta = \frac{\sigma_m}{\sigma_v} \]  

where \( \sigma_m \) is the first invariant of the stress tensor:

\[ \sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \]

and \( \sigma_v \) is the equivalent or von Mises stress:

\[ \sigma_v = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \]
Since, for plane stress state there is a relation between the stress triaxiality and the Lode angle parameter, the latter was determined based on the following equation:

\[ \xi = -\frac{27}{2} \eta \left( \eta^2 - \frac{1}{3} \right) \]  

(5)

The diameter of the specimen with the best results was 3 mm, the distance between the hole centres was 4.5 mm and the angle was 27 degree. Figure 4 illustrates a.) the strain distribution of the gage section; b.) and c.) the stress triaxiality and the Lode angle parameter as a function of von Mises strain. Since the damage model was not adjusted, further research needed to observe the fracture behaviour.

![Figure 4](image)

**Figure 4.** Results of the simulation of the best specimen: a.) the strain distribution of the gage section, b.) the stress triaxiality as a function of von Mises strain and c.) the Lode parameter as a function of von Mises strain

The simulation with the best design specimen, shows the deformation concentrated in the middle of the gage section during the process. The main strains correspond to the pure shear throughout the deformation. The value of the stress triaxiality and Lode angle parameter showed approximately the state of pure shear throughout the full process. Based on this simulation the specimen with the best results was milled from a table.

4. **Experimental setup**

The tests and the optical measurement on the new specimen were performed at the Bay Zoltán Nonprofit Ltd. in the Department of Material Testing. The tensile load was achieved by Instron E 10000 biaxial electro-dynamic testing machine, with a constant crosshead speed of 0.2 mm/min. The deformation of the specimen was recorded by a Photron Fastcam mini wX50 with a Titanar 5.6/100 objective, and 10 fps were applied for the measurement. Due to the distance between the gage sections, the deformation was measured only on the upper one.

5. **Results and discussion**

Physical experiments with optical measurements were performed, the results were summarized in figure 5. The strain distribution of the new, tensile loaded shear specimen and the modified smiley specimen is compared in the figure 5 a.) and b.) accordingly. While the strain concentrates in a narrow band in the case of the smiley specimen, a concentric deformation for the new specimen -according to the results of
the simulation- can be observed. This difference can be explained by the height of the shear zone, which is 2.36 mm for the smiley, and 1.5 mm for the new specimen.

Figure 5. Strain distribution of the new specimen a.) compared with the smiley specimen b.), and the strain path measured on the new specimen

The measured shear fracture strain was 0.94 for the new specimen, which is slightly higher than that measured by Mohr et al (0.86). In addition to the possible differences between the tested materials, the deviation of the shear fracture strains can be explained by the strain path illustrated figure 5 c.). The strain path can be characterized by $\beta$ and interpreted as:

$$\beta = \frac{\Delta \varepsilon_{22}}{\Delta \varepsilon_{11}}$$

where $\Delta \varepsilon_{11}$ and $\Delta \varepsilon_{22}$ are small increments of major and minor strains. In case of pure shear $\beta = -1$. As it can be seen on the figure, the strain path of the new specimen deviates slightly from the pure shear in the direction of compressive stress ($\beta = -1.03$), which can cause a higher fracture strain of the material.
6. Conclusions
The main purpose of this paper was to create a new, easy-to-manufacture tensile loaded shear specimen. The effect of laser-cut and EDM for the shear fracture strain of the modified smiley specimen were investigated and a large difference was observed. Therefore, to select the manufacturing technology for the new specimen, the effect of three different technologies to the boundary areas was examined. Based on the results of the hardness distribution and microstructure, and also considering the time- and cost effectiveness, the milling was chosen. The geometry of the specimen (more precisely the boundary of the gage section) was designed according to the possibilities of this technology. The specimen was optimized for DP800, changing the width, length, and angle of the gage section to the load axis. For the best results, the strain concentrated in the middle of the sheared zone, the stress triaxiality and the Lode angle parameter approached the pure shear stress state as a function of the evolving von Mises strain.

The results of physical measurement of the new specimen were compared with the literature, and negligible difference in the shear fracture strain was observed. It was found that the strain path does not fully correspond to the pure shear, so the angle between the loading direction and the gage section needs to be modified. The future plan is to apply a damage model to the simulations, to have better knowledge about the damage process, and fracture behaviour.

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References
[1] Keeler, S.P., 1961. Plastic instability and fracture in sheet stretched over rigid punches. (PhD. thesis). Massachusetts Institute of Technology, Boston.
[2] Goodwin, G.M., 1968. Application of strain analysis to sheet metal forming problemsin the press shop. Soc. Autom. Eng. (680093), 380–387. https://doi.org/10.4271/680093
[3] Hasek, V.: On the strain and stress states in drawing of large irregular sheet metal components, Berichte aus dem Institut für Umformtechnik, Universität Stuttgart, No. 25. (1973)
[4] Nakazima, K., Kikuma, T., Asuka, K.: Study on the formability of steel sheet, Yawata Technical Report, No. 264. (1968) September
[5] Maysam Gorji, Bekim Berisha, Niko Manopulo, Pavel Hora, Effect of through thickness strain distribution on shear fracture hazard and its mitigation by multilayer aluminium sheets; Journal of Materials Processing Technology 232 (2016) 19–33; http://dx.doi.org/10.1016/j.jmatprotec.2016.01.014
[6] Frieder Neukamm, Markus Feucht, André Haufe; Consistent Damage modelling in the process chain of forming to crashworthiness simulations; 7th LS-DYNA Anwenderforum, Bamberg 2008 Forming to crash
[7] A. Brosius, Q.Yin, A. Güner, and A.E. Tekkaya A new shear test for sheet metal characterization, steel research int. 82 (2011) No.4 DOI: 10.1002/srin.201000163
[8] ASTM Standard B 831-05 Standard Test Method for Shear Testing of Thin Aluminum Alloy Products. ASTM International, West Conshohocken, PA, doi:10.1520/B0831-05, www.astm.org.
[9] Z. Marciniak: Influence of the Sign Change of the Load on the Strain Hardening Curve of a Copper Test Subject to Torsion. Archiwum Mechaniki Stosowanj, 13 (1961), p. 743–751.
[10] Maysam Gorji, Bekim Berisha, Niko Manopulo, Pavel Hora; Experimental based crack failure criterion and its application in deep drawing operations. IDDRG 2015 conference shanghai china 2015, May 31- June 3
[11] Mohr, D., Henn, S., 2007. Calibration of stress-triaxiality dependent crack formation criteria: a new hybrid experimental numerical method. Exp. Mech. 47, 805-820.

[12] Mikos Tisza, Imre Czinege, comparative study of the application of steels and aluminium in lightweight production of automotive parts, International Journal of Lightweight Materials and Manufacture 1 (2018) 229-238; https://doi.org/10.1016/j.iijlmm.2018.09.001

[13] Yingbin Bao, Tomasz Wierzbicki; On fracture locus in the equivalent strain and stress triaxiality space; International Journal of Mechanical Sciences 46 (2004) 81–98 doi:10.1016/j.ijmecsci.2004.02.006

[14] Till, E., Hackl, B., 2013. Calibration of plasticity and failure models for AHSS sheets. In: Proceedings of the International Deep Drawing Research Conference IDDRG 2013

[15] Christian C. Roth, Dirk Mohr; Ductile fracture experiments with locally proportional loading histories; International Journal of Plasticity 79 (2016) 328-354 http://dx.doi.org/10.1016/j.ijplas.2015.08.004

[16] Frieder Neukamm, Markus Feucht, André Haufe; Consistent Damage modelling in the process chain of forming to crashworthiness simulations; 7th LS-DYNA Anwenderforum, Bamberg 2008 Forming to crash