Design of a simple shear test for large strains with sequential re-machining of the specimen edges

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Abstract. The simple shear test is a standard experiment used for the calibration of plasticity models. For thin sheets, the specimen can be as simple as a rectangular strip, or feature optimized geometries of the free edges. These enhancements are mainly motivated by the undesirable initiation of fracture from the free edges, which limit the usable strain range of the test. Previous studies have shown that fracture from the edges occurs due to a local stress state close to uniaxial tension in these areas. In an attempt to increase the maximum strain, a sequential simple shear test is proposed. The specimen is a sheet metal strip with two opposing cut-outs with rounded concave edges. The specimen is mounted in a shear testing device, composed of two jaws with a prismatic joint connection. The shear test protocol includes multiple two-steps sequences. First, an interrupted shear test is performed up to a given value of displacement. Second, the shear testing device, along with the clamped specimen, is positioned in a milling machine and the rounded free edges of the specimen are re-machined. The application of the proposed testing protocol is presented for three engineering materials. It is found that the valid range of this experiment (i.e. the maximum strains attained before specimen failure) can be substantially extended through repeated re-machining of the specimen boundaries.

1. Introduction

The accuracy of sheet metal forming numerical simulations is highly dependent upon the material behaviour model employed. This need is further emphasised by the recent development of advanced steels and aluminum alloys that can have high local plastic strains. Simple shear test, for example, has proved to be an efficient technique to evaluate the mechanical behaviour of sheet metal. However, the occurrence of fracture along the free edges of the specimen, as well as the tearing of the specimen from the clamping jaws limit the achievable maximum shear strain. As a result, the usable strain range is not large enough to enable an accurate choice of the hardening model and its proper parameter identification.

The existing shear techniques can be divided into two categories whether the shear is induced by a translation displacement, see figure 1 a and b, or a rotation displacement, see figure 1 c and d. A second classification can be performed from the geometry of the sheared area, with (see figure 1 a, b and c) or without free edges (without slits in the case of in-plane torsion, see figure 1 d). Note that for the latter, a circular groove is usually machined on the specimen surface in order to localise the strain on a narrow circular band. In the presence of free edges (see
figure 1 b, c), the shorter the gage section (for a given width), the more heterogeneous the stress state; thereby the determination of the plastic behaviour generally requires a hybrid numerical and experimental analysis. It should be noted that heterogeneity of the stress state may also arise during in-plane torsion experiments of slit free specimens due to material anisotropy.

Figure 1. Different categories of shear tests, inspired from Yin et al. [1] and Reyne et al. [2].

The simplicity of the simple shear test geometry and set-up and ability of fully experimental post-processing led us to favour it. Previous studies by Bouvier et al. [3] and An et al. [4] have shown that fracture from the edges is due to a stress state close to uniaxial tension in these areas. In an attempt to double the maximum strain, a sequential simple shear test is proposed. Each sequence is then composed of a simple interrupted shear loading step followed by a machining step, in order to reshape the free edges and remove the damaged material. In the present study, sequential simple shear experiments are performed on three engineering materials and discussed.

2. Experimental set-up
The specimen, see figure 2, is a sheet metal strip with two opposing cut-outs with rounded concave edges which diameter \(d = 3.4\) mm is very close to the shear gage section height \(h = 4\) mm. Shear cross-section refers to the minimal cross-section \(S = L \cdot t\). Materials thicknesses are larger than \(t \geq 0.8\) mm. Hereby, a shear gage height to sheet thickness ratio \(h/t < 5\) is ensured, and the shear gage length \(L > 37\) mm leads to a gage length to gage height ratio larger than \(L/h > 9\), in line with previous recommendations by Bouvier at al. [3]. In view of sequential machining and further specimen shortening, the initial length is chosen to be larger than 65 mm.

The shear test protocol includes multiple sequences. Prior to testing, the specimen is mounted in a shear testing device, composed of two frames (label 1 and 2 in figure 3), with a prismatic joint connection between each-other. Each sequence is composed of two steps. Step 1, figure 2, an interrupted shear test is performed up to a given value of displacement. This displacement corresponds to a strain between one third and half of the strain at load maximum of a monotonic shear test of the same material. During the second step, figure 2, the shear testing device along with the clamped specimen are positioned in a universal milling machine and the rounded free edges of the specimen are re-machined.

Shear tests are performed in a universal tensile machine (label 5 in figure 3), using a compression loading in order to avoid any clamping and un-clamping of the shear device. The shear device is made up of a fixed frame (label 1 in figure 3), and a movable frame (label 2). Both frames include a clamping jaw (label 6) with 4 clamping screws (label 7) in order to clamp the specimen (label 8). The shear load \(F\) is measured using the 50 kN load cell of the machine. The test is performed at a constant speed of the movable jaw of 0.5 mm/min ensuring a strain rate about 10\(^{-3}\)/s.
The samples for the experiments are waterjet cut as shown in figure 3 with milled free edges. To allow for Digital Image Correlation (DIC), a random speckle pattern with a white background and black speckles is applied. A 4 Mpx camera (label 3 figure 3; 2000x2000 px) equipped with a 50 mm f2.0 lens is used to record the images of the test at a frequency of 1 Hz with a spatial resolution of 50µ m/px. Two LED spots (label 4 figure 3) are used for illumination. Images from the experiments are post processed with the commercial DIC software Aramis (GOM).

The numerical and the experimental campaign led us to select a square subset size of 14 px and a step size of 8 px for the strain field calculations using a linear interpolation on a 3x3 points grid. These subset parameters enable to calculate the strain at the center on an area as small as 1.5x1.5 mm. The effective strain is computed from the principal strains by the equation:

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_I^2 + \varepsilon_{II}^2 + \varepsilon_I \varepsilon_{II}}$$  (1)

After the simple shear step, the device is clamped on the table of a milling machine (figure 4). Free edges are machined using a 3.4 mm diameter cylindrical mill. A two teeth micro-grain tungsten carbide end milling tool with sharp edges has been selected to minimise the surface hardening of the edge. The removed machined length is about 3 mm on each side.

3. Numerical simulation of the test, stress and strain evaluations

Finite element simulations are performed for the design of the test and validation of the measurement technique using the commercial FE solver LS-dyna (R10) and implicit time integration. Mesh is made of 0.1 mm length edge single integration point brick elements resulting in 40 elements through the gage section height, see figure 5. One side of the gage section is fully clamped while a rigid body translation displacement $u$ is applied to the opposite side. In order to gain detailed insight into the mechanical fields, a large range of engineering materials from soft aluminum alloys up to high strength steels and gage section length $L \in [30; 76]$ mm is involved. For the sake of brevity, only the main conclusions of the numerical study are presented.

Ideally, the shear stress and strain would be homogeneous along the specimen length. As already stated by An et al. [4], our calculations confirm that stress and strain homogeneity along the shear gage length evolve in opposite ways for rectangular and notched specimens. Nevertheless, the central element is in an almost perfect shear stress state and simple shear deformation. The goal of the shear test experimental measurement protocol is then to provide an accurate approximation of the shear stress and the shear strain at the central position from the load, the geometry of the specimen and the DIC displacement field. The shear stress is almost constant along the shear gage length of a notched specimen, while the shear strain is not homogeneous. For rectangular specimens, the shear strain is almost constant along the shear gage length, while the shear stress is not homogeneous. Hereby, for a notched specimen with gage length $L > 30$ mm, the shear stress of the central element can be approximated using the
average shear stress $\tau_{\text{ave}} = F/S$, and the error is found to be lower than 1.2% for effective strains up to 0.5 in the center of the specimen.

Thanks to the DIC parameters, the shear strain at the center can be calculated on a minimum area of 1.5x1.5 mm. The systematic use of the smallest ROI could lead to increase the noise of the strain value and the risk of mistake in the selection of the ROI on specimen surface. Hereby, the use of a notched specimen requires the definition of a proper Region Of Interest (ROI) around the center of the shear gage section for a robust and accurate calculation of an averaged strain which is an approximation of the shear strain of the element at the center. Considering a maximum discrepancy of $\pm 2\%$ of the effective strain, a capable $ROI_{2\%}$ is found to be 5 mm long and 2 mm high for the proposed geometries. Note that during our tensile test of the DC01 steel, the maximum discrepancy in stress was about $\pm 0.5\%$ for an engineering strain up to 0.5. Considering the behaviour law of the DC01 steel, a $\pm 0.5\%$ error in stress corresponds to a $\pm 2\%$ error in strain. In the following, the shear stress will be approximated using the averaged shear stress $\tau_{\text{ave}} = F/S$ value, the strain values will be approximated using the average strain in the $ROI_{2\%}=5 \times 2$ mm central area.
4. Experimental results
Sequential and monotonic shear test were carried out on DP450 steel \((t = 0.8 \text{ mm})\), AA2024-T3 aluminum alloy \((t = 1.2 \text{ mm})\) and DC01 steel \((t = 1 \text{ mm})\). For the latter, an additional in-plane torsion test was performed and already presented in Grolleau and al. [5].

|          | Sequence 1 | Sequence 2 | Sequence 3 | Sequence 4 | Sequence 5 |
|----------|------------|------------|------------|------------|------------|
| AA2024-T3| L = 76 mm  | L = 68 mm  | L = 63 mm  |            |            |
| DP450    | L = 77 mm  | L = 72 mm  | L = 66 mm  | L = 60 mm  |            |
| DC01     | L = 65.5 mm| L = 59 mm  | L = 50 mm  | L = 43 mm  | L = 37 mm  |

An example of the shear stress as function of the effective strain evolution is presented for a monotonic simple shear test and a sequential shear test in the case of the DP450 steel in figure 6. A 0.2 shear step increment value was used for the sequential test. For both tests the initial specimen length is 77 mm, see Tab. 1. In the case of the monotonic test, a maximum stress is reached at an effective strain value about 0.4, and the hardening rate is monotonically decreasing during the test. It is clear from figure 6 that even with the interruption of the test and the re-machining of the free edges the sequential testing enables to recover the same behaviour as the monotonic test. Moreover, the sequential test result doesn’t exhibit any saturation of the shear stress, and the hardening rate is almost constant up to an effective strain of 0.7. Similar results are obtained for the three materials.

The homogeneity of the mechanical fields is presented in the case of the sequential test of a DC01 steel in figure 7 and 8 showing the evolution of the effective strain as a function of the position along and across the shear gage section respectively. The 5 curves, in blue solid lines, correspond to the final stage of each sequence, and the corresponding shear gage lengths are given in Tab 1.

In the case of the sequences number 2 and 4, the absolute values of the major and the minor strains are plotted as function of the position along the gage section in figure 7 using green and red solid lines. All along the test, and along the gage section, major and minor strains have almost the same absolute value. The discrepancy is negligible in the central area compared to
the noise in strain, and increases towards the edges up to a strain discrepancy about 0.03, which confirms the simple shear kinematics state hypothesis in the center. As discussed in the section 3, the effective strain field is not homogeneous, with a pronounced convex shape along the gage length and a slightly concave shape across the gage section. These experimental results confirm that a reduced ROI is required for the approximation of the strain value at the center of the specimen.

In figure 9, the relative error from the strain at the specimen center is plotted for various ROI sizes. The reference value of the strain at the center is calculated on a 2x2 mm ROI at specimen center. When the ROI corresponds to the full specimen surface (see blue solid line), the error is as high as 20% at the beginning of the test. Each machining step leads to a drop in the error, see for example between sequences 1 and 2. The smaller the ROI, the smaller the error, and the error is lower than 2% for a ROI size of 5x2 mm. Note that for smaller sizes, the signal to noise ratio can become prohibitive.

The figures 10 anf 11 show the results obtained in the case of monotonic, sequential and in-plane torsion of the DC01 steel. The figure 10 (left) focuses on the repeatability obtained

![Figure 7](image7.png)  ![Figure 8](image8.png)  ![Figure 9](image9.png)
using monotonic shear test. The same conclusions as for the DP450 steel can be drawn, with a maximum load occurring at a strain about 0.6 and a decreasing hardening rate in the case of the monotonic shear. The stress vs. strain curve is again characterised by a concave shape and the occurrence of a maxima in stress. The error bars indicates the min and max values obtained over three repeats, and show a large discrepancy for effective strain above 0.45. This value corresponds to the strain at which monotonic and sequential results diverge. The sequential result is plotted in green solid lines up to a strain value about unity. A shear strain increment of 0.2 is used, highlighted with solid circles.

The repeatability of the sequential shear test results can be appreciated in figure 10 (right) for three repeats. The dispersion is slightly increasing at large strain. For example at an effective strain of 0.8, see figure 10 (e), the maximum dispersion is 15 MPa. This corresponds to the dispersion observed in the monotonic tests at an effective strain of 0.4.

The repeats have been performed using various shear strain increments values from 0.2 up to 0.35. The effect of the shear strain increment value can be appreciated comparing the test number 2, blue curve (shear strain increment about 0.2), and test 1, red curve (shear strain increment about 0.35). At a strain about 0.35, see figure 10 (d), the test 1 is at the beginning of its second sequence and a drop in the shear stress value is clearly visible. At the same strain, the test number 3 is at the beginning of the third sequence, and the use of smaller shear step increment lead to negligible drop in stress. From our experiments, it seems that an optimal shear step increment value is about one third and half the strain at force maximum of the corresponding monotonic shear test.

Nevertheless, whatever the length of the shear strain increment, a stress maximum always occurs during the last sequences. This is attributed to the initiation of fracture along the free edges. From sequence to sequence, this phenomenon occurs closer to reloading. The test is stopped when the fracture from the side starts almost immediately after reloading.

Figure 10. Comparison of monotonic shear tests (red solid line) with sequential (green solid line) shear test on DC01 steel (left), repeatability of the sequential shear test on three tests (right). Each end of shear step is highlighted with a dot at the corresponding strain value, vertical position is meaningless.

The figure 11 shows the comparison of the monotonic, sequential and in-plane torsion tests results in terms of stress versus strain. All results agree well up to an effective strain of 0.4.
Above that strain, the sequential and the torsion test results only agree up to an effective strain of 0.85.

![Graph showing comparison of simple shear and torsion results on DC01 steel](image)

Figure 11. Comparison of simple shear (monotonic, red solid line; sequential, green solid line) and in-plane torsion (black solid line) results on DC01 steel, shear stress vs effective strain.

5. Conclusion
In order to extend the shear strain range achievable with the simple shear test, we propose a sequential shear test protocol. The specimen is a sheet metal strip with two opposing cut-outs with rounded concave edges. The shear test protocol includes multiple two-steps sequences. First, an interrupted shear test is performed up to a given value of displacement. Second, the rounded free edges of the specimen are re-machined. Special care is devoted to the position of the specimen by transferring the entire testing frame from the testing to the milling machines. Stress versus strain curves obtained from monotonic tests are characterised by the occurrence of a stress maxima, a monotonically decreasing hardening rate and an increasing dispersion of the results close to the maximum stress. On the contrary, sequential tests results lead to an almost constant hardening rate and a higher repeatability of the results up to a maximum strain value which is twice higher than for the monotonic test. After a numerical study of the experimental set-up, the sequential test has been applied to three engineering materials. In the case of a DC01 steel, the results have been validated from against a newly-developed in plane torsion test.

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