Characterizing plasticity and fracture of sheet metal through a novel in-plane torsion experiment

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Abstract. In-plane shear specimens typically feature free gage section boundaries along which the state of stress deviates from that of pure or simple shear. As a consequence, the geometry of in-plane shear specimens needs to be carefully chosen to avoid any early fracture initiation from the free boundaries, before the actual failure strain for shear is reached at the specimen center. From this perspective, disc specimens for in-plane torsion experiments offer a significant advantage: they do not feature any free boundaries. However, detailed analysis suggests that circular groove need to be introduced (local thickness reduction) to ensure a strain localization away from the clamped specimen shoulders. In most existing in-plane torsion tests, the specimen is clamped on the inner diameter by applying out-of-plane compression to avoid any slipping. In such configurations, it is impossible to monitor the entire sheared circumference with cameras for digital image correlation. It is the goal of the present work to develop in-plane torsion test using grooved specimens with full optical access to the specimen for 2D or 3D DIC measurements. Furthermore, the experimental set-up will be designed for plasticity and fracture characterization at strain rates of up a few 100/s. Its main feature is a new clamping technique. After identifying a suitable specimen geometry through finite element simulations, experiments are performed on specimens extracted from aluminum alloys and steels sheets. The experimental campaign includes proportional loading, reversed loading and strain rate jumps. The full optical access to the sheared gage section area also enables the discussion of the effects of plastic anisotropy on the strain fields in in-plane torsion experiments. The results from the in-plane torsion experiments are also compared with the fracture strain measurements from in-plane shear experiments performed in a conventional uniaxial loading frame.

1. Introduction
There is a constant quest for reliable experimental data characterizing the plastic and fracture response of materials. Major advances have been made in developing reliable techniques for determining the strains to fracture from experiments for stress states from uniaxial to biaxial tension. However, for shear loading conditions with stress triaxialities $\eta<0.33$, considerable experimental challenges need to be overcome. Numerous flat specimens with shear loading orientated along one material direction and with or without thickness reduction have been proposed, as conceptually shown in Fig. 1a.

Another path is pursued by in-plane torsion experiments, in which a gage section clamped between an inner and an outer grip is deformed by rotational loading (Fig. 1b-d). The first in-plane torsion test was proposed by Marciniak (1961) \cite{1} with the aim to identify a material’s work hardening, its
Bauschinger effect and the strain to fracture. Sowerby et al. (1977) [2] and Tekkaya et al. (1982) [3] performed a more complete analysis of the shear strain and stress fields during the in-plane torsion test of a flat disc. The main drawback of the standard in-plane torsion test of flat specimen is that shear strain localization may occur at the inner clamping diameter. To overcome this drawback and to reduce the sheared section size and the loading torque, some researchers machined annular slits on the specimen (Fig. 1c) [4], thereby accepting inhomogeneous strain fields and possible fracture from the free edges. Yin et al. [5] and Traphöner et al. [6] thoroughly analyzed the advantages of reducing the sample thickness with a grooved in-plane torsion geometry (Fig. 1d).

In the present work, an enhanced in-plane torsion test is presented using grooved specimens with full optical access to the specimen gage section for DIC measurements. It provides an almost perfectly proportional loading path for simple shear loading. Thanks to a special clamping technique, it will also be suitable for characterizing ultra-high strength steels over a wide range of strain rates. A numerical analysis of the test is carried out before performing experiments with proportional and reverse loading, as well as strain rate jump tests. The results from the in-plane torsion experiments are also compared with fracture strain measurements from recently developed shear experiments performed in a conventional uniaxial loading frame (see Roth and Mohr [7] for details on the technique).

Figure 1. Specimen geometries for shear tests. (a) flat in plane shear specimen acc. ASTM B831. (b) flat in-plane torsion disc specimen. (c) flat in-plane torsion disc specimen with slits and (d) with a groove free of slits. A schematic view of two initially parallel lines, perpendicular to the shear area are plotted in their deformed configuration in order to highlight the sheared zone.

2. Design of in-plane torsion experiment

2.1. Specimen clamping and loading

In existing in-plane torsion tests, the inner clamping part is compressed between two shafts, e.g. Yin et al. use a universal testing machine to apply a sufficient preload on the inner clamping area to avoid slipping of the specimen. With this configuration optical access perpendicular to the specimen surface is difficult to obtain, thus requiring the use of 3D DIC. Here a new clamping technology with a single shaft with a threaded end is presented (Fig. 2a) while the clamping load is applied with a single nut. In this case and especially for high strength materials, a frictional connection at the sample surface does not suffice to transmit enough torque to perform the test. Hence a form closure connection is created by machining 90 female radial grooves on the inner clamping surface of the specimen (Fig. 2b). In order to transmit the torque from both sides of the specimen, two washers with 90 male face splines are used between the driving shaft and the specimen. A prismatic joint is created between the driving shaft and the washers by using a series of axial pins (Fig. 2b). As direct contact between the specimen and the pins would cause radial loading of the specimen, a sufficient gap between the pins and the specimen needs to be maintained.
2.2. Specimen groove design

The standard groove geometry is a circular cut-out resulting in a torus as its revolved shape [5]. A finite element model of a 5° section of the torsion sample with cyclic boundary conditions is created, using an isotropic J2 plastic behavior resembling a DP980 steel. The numerical study reveals that the circular groove leads to a pronounced gradient in the effective strain field between the top and the bottom face of the groove, irrespective of the groove radius. Fig. 3a shows the evolution of the effective groove strain concentration ratio as a function of the groove radius $r_g$. Scatter bars refer to the minimum and maximum ratio obtained for effective strain levels in the range [0.1:0.8]. In addition, this geometry leads to a relatively thin shear band of the size of the smallest specimen thickness and no homogeneously stressed volume. To reduce the strain concentration on the bottom of the groove and obtain a volume of constant shear stress we develop a modified groove geometry, consisting of a conical section enclosed by two radii $R_1$ and $R_2$ (Fig. 2b). While from theory this ring should have the shape of a paraboloid, the short radial length of ca. 1mm between $R_1$ and $R_2$ justifies an approximation with a cone. Given a conical length longer than half the minimum specimen thickness ($2(R_2 - R_1) > t_s$) the modified geometry drastically reduces the groove strain concentration ratio to a value lower than 2.3% for groove radii between 3 and 5mm. Fig. 3b shows a distribution of the stress field for the converged mesh with an element length of $l_e=0.025$mm for the final specimen geometries as shown in Fig. 2a. To keep the results as representative as possible, a minimum thickness of the grooved section of more than half of the sheet thickness is maintained.

3. Experiments

3.1. Experimental procedures and post-processing technique

The initial specimen geometry is machined using waterjet cutting. The use of a ball mill with perpendicular axis to the specimen surface is not considered, as this technique would lead to a null cutting speed and poor cutting capacities at the bottom of the groove, the location where shear fracture is expected to occur. Although turning will likely generate circular strips on the specimen surface (the direction fracture is expected to occur), here we make use of a lathe with a face grooving tool holder.
and a large nose radius insert of 1.5mm with sharp normal cutting edge \( r_n = 15\mu m \) for machining. This leads to a very low roughness \( R_t < 3\mu m \) and arithmetic average roughness \( R_a \approx 0.5\mu m \), measured using a Leica confocal microscope along a 2 mm radial line length.

![Figure 3. Results from the numerical analysis: (a) Study of groove effective strain concentration ratio as function of the groove radius for standard and new geometries. (b) Cut-view of the mesh used for the numerical study showing the homogeneity of the equivalent stress field.](https://example.com/figure3.jpg)

All experiments are performed on a standard 2000Nm Zwick torsion machine. An Oldham transmission is used to ensure that a pure torque loading is applied to the shaft and to the inner clamping area of the specimen, preventing any out of plane loading. The specimens are tested under rotation control, with rotation speeds in the range \([0.025:2.5]\) /s. The mean shear stress is calculated from a torque load cell. Before each test, a fine speckle pattern is applied to the side without a groove. Images are taken with a 12MP camera in conjunction with a Nikon lens (f2.8, 28mm) at a frequency of 1Hz resulting in a spatial resolution of approximately 22µm/pixel. The effective surface strain is then calculated based on the principal Hencky strains obtained in VIC, and if a simple shear strain field is obtained, the so-called shear angle or shear ratio \( \gamma \) can be calculated.

\[
\bar{\varepsilon} = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_i^2 + \varepsilon_j^2 + \varepsilon_k^2} = \frac{2}{\sqrt{3}} \sinh^{-1}\left(\frac{\gamma}{2}\right)
\]

### 3.2. Application of the device in selected plasticity experiments

The applicability of the experimental setup for large strain plasticity testing is presented for DC01 deep drawing steel. While uniaxial tensile tests cannot be evaluated after the onset of necking \( (\varepsilon \approx 0.2) \) and the bulge tests fail at \( \varepsilon \approx 1.0 \), the present in-plane torsion test has been successfully conducted up to effective strain of \( \bar{\varepsilon} = 2.15 \) and a corresponding shear ratio of \( \gamma = 6.3 \) without any buckling of the specimen. The Major and minor eigenvalues the Hencky strains differ by only 2%, indicating an almost perfect simple shear strain state. The strain rate jump test capability of the device is shown in Fig.4a with three monotonic tests and a jump test with a maximal recovery error in stress of 2.5%. The repeatability of the experiments is depicted with two tests performed at a mean shear rate of 0.003/s. The quality of the achieved clamping and torque transmission is shown Fig.4b obtained under cyclic loading. On the torque - actuator rotation angle curve (solid red curve, Fig.4b), the change in torque sign leads to a measurable play of only about 0.22° and an apparent specimen stiffness of about 40% of the theoretical value.
3.3. Application of the device in selected fracture experiments

The applicability of the new in-plane torsion setup to determine the fracture strain for simple shear loading for high strength materials is shown on a DP980 AHSS specimen with 1.5mm initial thickness and a groove thickness of 0.78mm (Fig.5a). The maximum torque at fracture is approximately 1800Nm, resulting in an equivalent stress of about 1200MPa assuming an isotropic J2 material. Fig.5c shows the evolution of the maximum effective strain along the specimen circumference at the time step prior to fracture, indicating that fracture occurs at a location initially approximately 45° from the rolling direction at an effective strain of about $\bar{\epsilon}_f \approx 0.84$. The result from the torsion test is compared to experiments on a recently developed in-plane shear geometry [7].

![Figure 4](image1.png)

**Figure 4.** Experimental results for DC01 steel: (a) Torque – effective strain plot for three different strain rates and respective strain rate jump test. (b) Torque – shear ratio (dashed blue line) and torque – actuator angle (red solid line). Note the very small compliance when passing zero torque.

![Figure 5](image2.png)

**Figure 5.** Experimental results for DP980 steel (a) Effective strain contour plot of the torsion test and (b) effective strain contour plot of the in-plane shear test. (c) Comparison of the fracture strain for torsion and in-plane shear specimens, whiskers corresponds to minor and maximal measured values. For orientations 0° ($\bar{\epsilon}_f = 0.78$) and 90° ($\bar{\epsilon}_f = 0.77$) the torsion test does not reach the fracture strain obtained in the shear experiment, while at 45° ($\bar{\epsilon}_f = 0.84$, Fig.5b) the fracture strains agree well. In the
torsion test fracture will occur at a given angle w.r.t. the rolling direction of the specimen, but this does not necessarily coincide with the fracture limit for all material orientations. The obtained effective strain – orientation plot has to be considered as a lower bound of the strain to fracture for the material.

4. Discussion and conclusion

An in-plane torsion experiment is developed to determine the plastic and fracture behavior of modern engineering materials. The clamping device uses form closure between the specimen and the driving shaft by means of a single nut. All parts of the driving system can therefore be positioned on one side of the specimen, thereby giving full access to the opposite side. This enables the observation of the whole specimen surface, respectively the whole shear zone circumference, with a single camera. Two-dimensional Digital Image Correlation is used to extract the material deformation up to very large strains, e.g. $\varepsilon = 2.15$, $\gamma = 6.3$ for DC01, and for strain rates ranging from 0.001/s to 0.1/s. The strain field is not constant along the circumference of the specimen, which is attributed to the anisotropy of the material. The new clamping system assures a high rigidity of the device, making it suitable for cyclic loading as well as for testing ultra-high strength steels with a permissible torque of 2000Nm for a radius of the sheared zone of 23mm from the shaft axis.

In-plane torsion fracture experiments are performed on a DP980 steel and compared to results from a set of optimized in-plane shear fracture specimens extracted in 0°, 45° and 90° to the rolling direction. A good agreement between the two testing techniques is obtained, with the torsion failing in the 45° direction.

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