Extending the annular in-plane torsional shear test specimen to applications at high strain rates

Muhsin Osman[1], *Trevor John* Cloete[1*], and *Ernesto Bram* Ismail[2]

[1]Blast Impact & Survivability Research Unit (BISRU), Department of Mechanical Engineering, University of Cape Town (UCT), South Africa
[2]Centre for Research in Computational and Applied Mechanics (CERECAM), Department of Mechanical Engineering, UCT, South Africa

Abstract. In-plane torsional shear testing is a well-established material testing technique in the metal forming community. The corresponding specimen is designed to be machined from sheet metal with a continuous annular shear zone intended to deform in simple shear. Consequently, there are no geometric discontinuities or "edge-effects" to induce volumetric changes or instabilities with the result that large true plastic strains up to 1.0 can be achieved. This paper presents an extension of the in-plane torsional shear test to the dynamic regime. Dynamic experiments were performed using a torsional split Hopkinson bar (TSHB) on specimens manufactured from Al 1050 H14. The experimental results show that the adopted technique can be used to determine the material behavior accurately and reliably in the dynamic regime.

1 Introduction

The accurate determination of material properties of sheet metal forms the basis for numerical process analysis [1]. Experimental tests are therefore required to determine stress vs strain values, and to do so up to high values of true strain. This is particularly significant in sheet metal forming where strain reaches values beyond 1 [1]. The single-sided shear specimen [2], shown in Figure 1(a), and Miyauchi specimen [3], shown in Figure 1(b), are two of the most commonly used specimens for shear testing. However, the free edges result in the gauge section not being in pure shear and crack initiation is possible at the corners of these edges. According to Yin et al. [4], an ideal mechanical test should have an in-plane pure shear stress state, a controlled location for crack initiation, and the shear stress and shear strain should be determined without the need to revert to an inverse procedure. An added feature would be the possibility for the specimen to be machined from sheet metal. The tubular specimen, shown in Figure 1(c), has been used extensively in dynamic tests. However, while the specimen has a continuous shear zone and thus no edge-effects, it cannot be manufactured from sheet metal. The in-plane torsional test meets all these requirements. It was first introduced by Marciniak and Kolodziejski to investigate ductile failure in planar sheets [5]. Their round sheet specimen, shown in Figure 1(d), is clamped concentrically at

* Corresponding author : trevor.cloete@uct.ac.za

the centre and the outer rim, with deformation occurring in the ring-shaped area between these clamping surfaces. Yin et al. proposed a modification to the original design by incorporating circular grooves [4], shown in Figure 1(e). Deformation is limited to the grooved portion of the specimen. The continuous circular groove removes the possibility of edge-effects while the low overall thickness made manufacturing out of sheet metal possible. Since the material properties may vary through the thickness of the sheet metal, it may be advantageous to have an optimal cut depth of over 50% of the thickness when cutting from one side. The relatively simple specimen geometry allows for the direct full field measurement of equivalent strain via digital image correlation (DIC). The specimen also allows for the testing of thick sheets due to the reduced cross-section requiring a lower shearing torque and large shear strain data can be obtained to support numerical analysis without the need for flow curve extrapolation. To date, the literature appears to have focused on testing in the quasi-static regime. However, since metal forming extends beyond the quasi-static regime, it is necessary to obtain dynamic data.

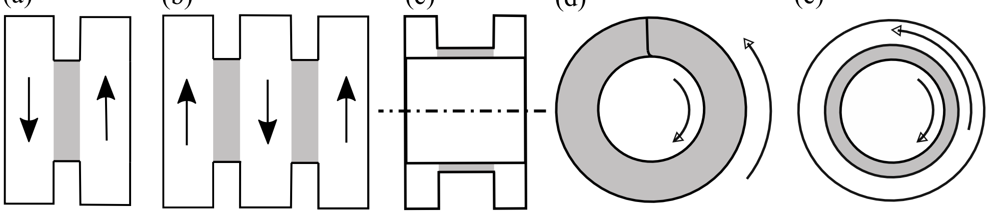

Figure 1: Shear test specimens for the characterisation of plastic behavior of sheet materials: (a) Single sided shear test [3], (b) Miyauchi shear test [4], (c) Tubular specimen (d) Marciniak round sheet specimen [5], and (e) In-plane torsion test [1]. The grey colour in the figure represents the gauge section of the specimens.

The average shear stress, τ, at a given radial position, r, in the gauge section for a specimen manufactured from an isotropic material can be calculated using Eq. (1) where T is the measured torque, and h is the gauge section thickness. The highest shear stress is located near the inner clamping surface, decreasing with increasing distance from the rotation centre. The shear strain, γ, is described by the change in slope of an initially radial line for any radial position r where θ is the angle of rotation and is calculated using Eq. (2). However, for planar anisotropic materials simply using Eq. (1) will result in an error due to the measured torque being an integral value over the whole circumference, thus it does not distinguish the material behaviour in different orientations. Therefore, using the Hill anisotropic yield criterion [6], the normal anisotropy, r_n, defined as the ratio of logarithmic strain in width and thickness directions [11], can be accounted for. The equivalent stress, σ_f, and equivalent plastic strain, ε_{eq}, is then calculated using Eq. (3) and Eq. (4).

$$\tau = \frac{T}{2\pi r^2 h} \quad (1); \quad \gamma = r\frac{d\theta}{dr} \quad (2); \quad \sigma_f = \sqrt{3}\,\tau\sqrt{\frac{2(2r_n+1)}{3(r_n+1)}} \quad (3); \quad \varepsilon_{eq} = \frac{\gamma}{\sqrt{3}}\sqrt{\frac{3(r_n+1)}{2(2r_n+1)}} \quad (4)$$

The torsional split Hopkinson bar (TSHB) system allows for reliable high strain rate testing of materials up to 10^4 /s [7]. The TSHB was originally introduced to verify strain-rate effects observed in tests using the compression Hopkinson bar [7]. The basic TSHB system consists of an incident bar and a transmission bar with the specimen connecting the two bars. A wave pulse (incident wave) is generated in the incident bar and propagates towards the specimen. Upon reaching the specimen, part of the incident wave is transmitted through the specimen into the transmission bar (transmitted wave) while part is reflected back along the incident bar (reflected wave). Strain gauges placed on both bars record the three waves which are used to infer the dynamic stress and strain.

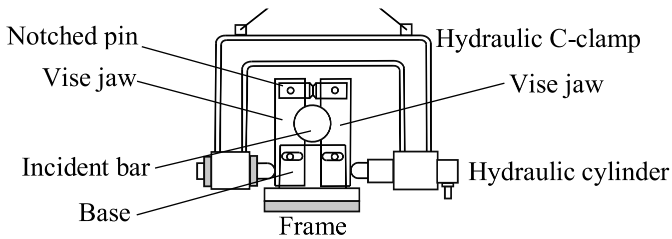

Figure 2: TSHB clamping mechanism by Pao & Gilat [8].

The most commonly used method for inducing a travelling wave in the incident bar is the stored elastic energy method which involves the mechanical release of a stored torque. The stored torque is generated by twisting one end of the bar and holding the torque, a distance away, via a clamping mechanism. Pao & Gilat [8] designed the clamp, shown in Figure 2, which was a variation of the clamp designed by Hartley et al. [9]. The clamp design incorporates a C-clamp with a fracture pin holding the two arms together at the top and both arms sliding at the bottom. After the desired torque is applied, the hydraulic pressure is increased until the fracture pin ruptures, thereby releasing the torque.

The purpose of this paper is to report on quasi-static and dynamic testing using the in-plane torsional specimen. Section 2 describes the experimental techniques, including the specimen design. The experimental results are shown in Section 3, followed by a discussion of the results in Section 4.

2 Experimental techniques

2.1 Specimen design

Figure 3 shows a detailed description of the modified in-plane torsional specimen. The holes in the centre portion function as the mounting points of the specimen to the incident bar, while the peripheral castellations interface with the output tube. The centre hole ensures concentric positioning of the specimen and the reverse face provides a flat surface suitable for full field diagnostic techniques. The expansion holes are used to ensure good mechanical connection (via self-tapping screws) with the slits in the castellations allowing for the holes to hinge about the edge of the slit. The specimens have gauge section thicknesses ranging from 0.2 mm to 0.4 mm and gauge section widths ranging from 0.5mm to 5 mm.

(a) Gauge section
(b) Outer castellation for output tube mounting
(c) Input bar mounting holes
(d) Expansion hole for removal of backlash

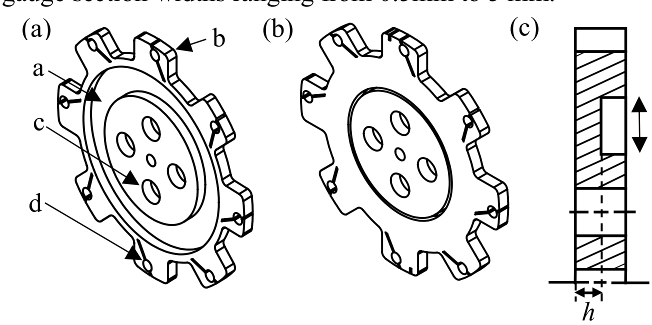

Figure 3: In-plane torsional specimen: (a) Obverse face of wide gauge section with key features labelled, (b) Obverse face of narrow gauge section, and (c) Top half of section view with gauge section dimensions labelled.

2.2 Quasi-static torsional system and torsional split Hopkinson bar design

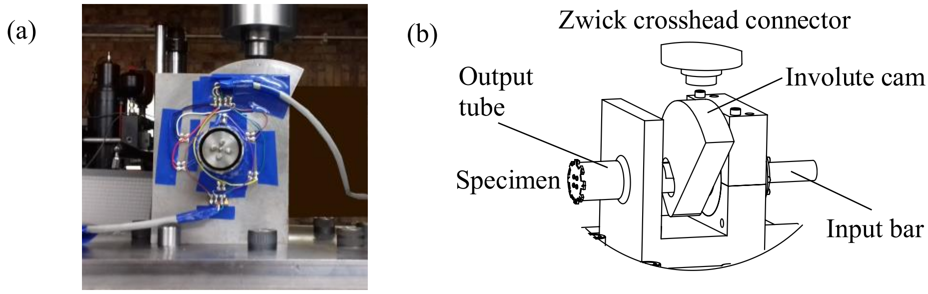

Figure 4: QSTS: (a) Image of system , and (b) schematic with key features.

Two different testing systems are used to cover a range of strain rates. These are a novel quasi-static torsional system (QSTS) and TSHB configuration. The described systems share two similarities. Firstly, the input/incident bar having four equi-spaced 4mm pins for the input end mounting of the specimen as well as a 2 mm pin located at the centre to assist in locating the specimen when mounting. Secondly, the castellations machined to the output/transmission tube which function as the output end mounting of the specimen. The QSTS, shown in Figure 4, is assembled on a Zwick 1484 universal testing machine. The input bar is rotated by means of the Zwick crosshead contacting the involute cam attached to the input bar, while the outer housing is fixed to the machine. The torque on the outer housing is measured using a full-bridge strain gauge configuration. The angle of rotation is inferred from the Zwick crosshead displacement and the known arm length. The involute cam provides a linear relationship between the vertical displacement of the Zwick crosshead and the angle of rotation of the input bar. The shear strain rate capability of the machine is governed by the Zwick crosshead speed as well as the specimen gauge width.

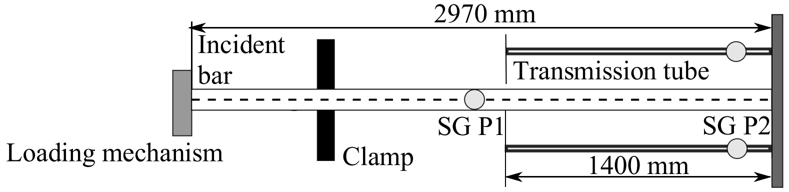

Figure 5: Schematic representation of the torsional split Hopkinson bar apparatus.

$$\dot{\theta}_i = \frac{T_i(\tau) - T_r(\tau)}{(pJc)_i} \text{ and } \dot{\theta}_t = \frac{T_t(\tau)}{(pJc)_t} \;\; (5); \; \dot{\gamma} = \frac{r_i(\dot{\theta}_i - \dot{\theta}_t)}{W} \;\; (6); \; \gamma = \int_0^t \dot{\gamma}(t)dt \;\; (7); \; \tau = \frac{T_t(\tau)}{2\pi r_i{}^2 h} \;\; (8)$$

Dynamic testing was conducted using a modified stored torque TSHB setup. A schematic representation of the system is shown in Figure 5. The incident bar is manufactured from aluminium 7075 T6, with a diameter of 20 mm and a length of 3 m. The transmission tube is manufactured from aluminium 6063 T6, with an outer diameter of 38.1 mm and a wall thickness of 1.62 mm. The length of the transmission tube is 1.4 m. Under the assumption of one-dimensional wave propagation, dynamic equilibrium and elastic bars, equations (5)-(8) can be applied. The angular velocity of the incident bar, $\dot{\theta}_i$, and the angular velocity of the transmission tube, $\dot{\theta}_t$, are determined using Eq. (5) where $T_i(\tau)$ is the measured incident wave, $T_r(\tau)$ is the measured reflected wave, $T_t(\tau)$ is the measured transmitted wave, ρ is the density of the bar, J is the second polar moment of inertia, and c is the shear wave speed. The average shear strain rate, $\dot{\gamma}$, is calculated using Eq. (6) where r_i is the inner-most radius of the gauge section and W is the specimen gauge width. The average shear strain of the specimen, γ, is obtained using Eq. (7). Finally, the shear stress in the specimen, τ, is determined using Eq. (8) where h is the specimen gauge section thickness. The torque generation system incorporates a hydraulic jack which rotates the loading arm when extended. This action imparts a torsional load onto the incident bar. The fracture-pin clamping mechanism used is based on the one developed by Pao & Gilat [8].

3 Experimental results

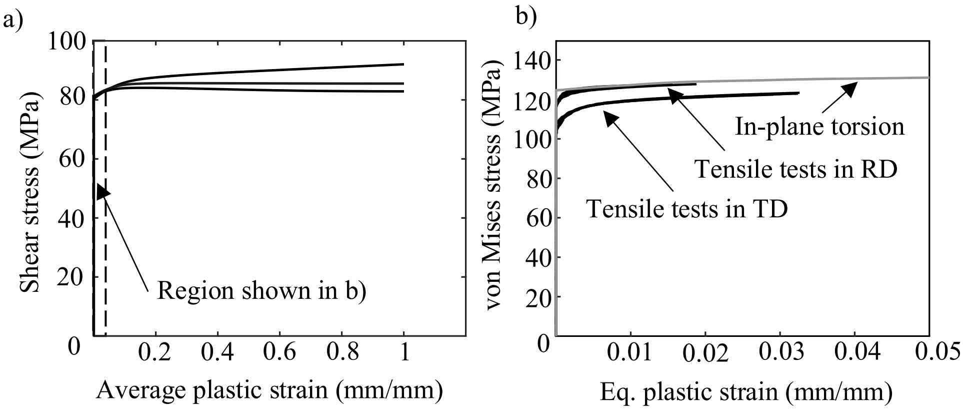

Figure 6: Comparison of experimental flow curves from tensile tests and in-plane torsion test: (a) 3 in-plane torsion tests having same specimen geometries, and (b) 5 tensile tests in rolling direction (RD) and 4 in the transverse direction (TD) against a single in-plane torsion test to limited strain.

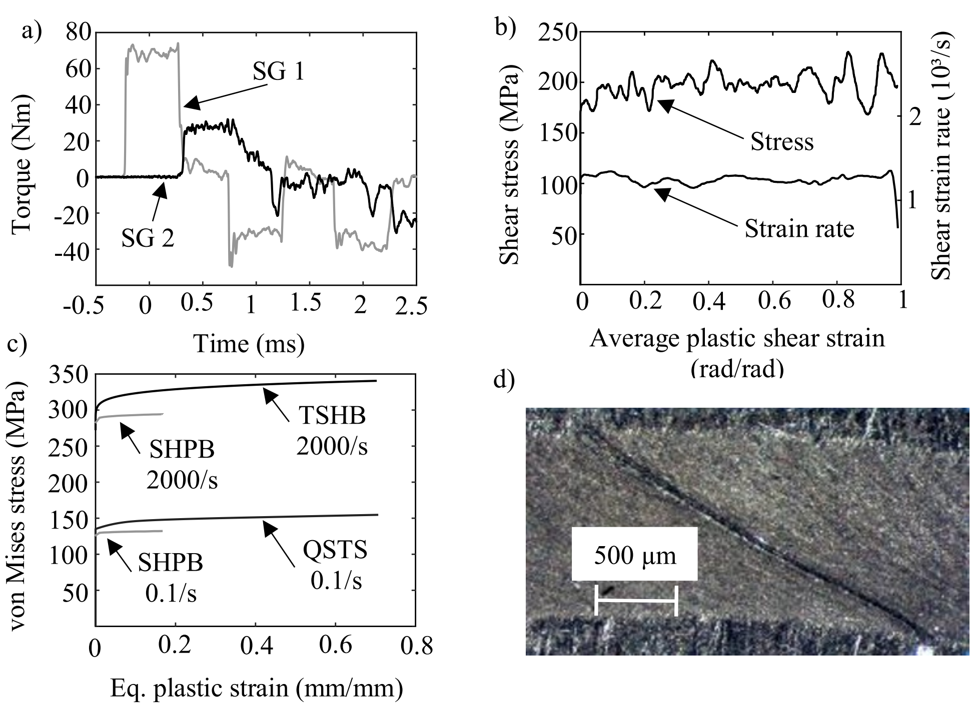

Figure 7: Typical test data: (a) Raw signals measured by strain gauges for TSHB test, (b) Shear stress and shear strain rate against strain for TSHB test, (c) Comparison of QSTS and TSHB test data with known literature [10], and (d) Microscope image of deformed specimen associated with a QSTS test.

4 Discussion

Figure 6 (a) shows the results of three in-plane torsion tests where the crosshead speed and dimensions of the specimens were the same. Shear yield stresses were approximately 80 MPa with the plastic strain limited by the manual termination of the experiments. For comparison, tensile tests were conducted on rectangular cross-section dogbone tensile specimens manufactured from the same material. The results are shown in Figure 6 (b) and indicate the greater plastic strain potential the in-plane torsion test has over the tensile specimen. Figure 7 (a) shows the typical raw data obtained from the strain gauges. Consistent rise-times of approximately 20 μs were obtained with durations governed by the position of the clamp. Significant oscillations were observed in the incident wave which may indicate imperfect clamp release. Figure 7 (b) shows the shear stress and shear strain rate as a function of shear strain. Specimens with a smaller gauge section width reached strain rates of up to 10^4 /s and nearly homogeneous deformation. Shear yield stresses were approximately 170 MPa indicating the strain rate sensitivity of the material tested. Figure 7 (c) shows a comparison of the quasi-static and dynamic test data. The results confirm the known strain rate sensitivity of Al 1050 H14 with the measured stress levels obtained from the TSHB tests corresponding well with SHPB tests done on the same material [10]. Lastly, Figure 7 (d) shows a deformed specimen with a near uniform strain distribution.

5 Conclusion

The modified in-plane torsional shear test specimen together with the configuration of the QSTS and TSHB systems has been shown to be capable of testing sheet metal at a wide range of strain rates. The specimen design and nested configurations of both the QSTS and TSHB are compact with ease of use and diagnostic access. The experimental results are reliable and consistent to high values of strain, both for the QSTS and TSHB, showing good agreement with similar work found in literature. There is great potential for further development of the in-plane torsional shear test specimen for the testing of sheet metal.

References

[1] H. Traphöner, T. Clausmeyer, A. E. Tekkaya, J. Mat. Proc. Tech., **257**, 278 (2018)
[2] S. Bouvier, H. Haddadi, P. Levée, C. Teodosiu, J. Mat. Proc. Tech., **172(1),** 96 (2006)
[3] K. Miyauchi, Sci. Pap. Inst. Phys. Chem. Res.(Jpn), **78(3)**, 27 (1984)
[4] Q. Yin, C Soyarslan, K. Isik, A. E. Tekkaya, Int. J Sol. Struct., **66**, 121 (2015)
[5] Z. Marciniak, Arch. Mech. Stosowanj, **13**, 743 (1961)
[6] R. Hill, Proc. Roy. Soc. London. Series A. Math. and Phy. Sci., **193(1033)**, 281 (1948)
[7] G. Subhash, ASM Handbook, **8**, 1138 (2000)
[8] Y. Pao, A. Gilat, Acta metal. et mater., **40(6)**, 1271 (1992)
[9] K. A. Hartley, J. Duffy, R. H. Hawley, ASM metals Handbook, **8**, 218 (1985)
[10] H. G. Noh, W. J. An, H. G. Park, B. S. Kang, and J. Kim, Int J Adv Manuf. Technol., **91**, 629 (2017)
[11] B. M. Hance, J. Mat. Eng. Perf., ***14*(5)**, 616 (2005)