

Fracture Characterization of Automotive Alloys in Shear Loading

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ABSTRACT

Two different shear sample geometries were employed to investigate the elastoplastic and failure behaviour of three automotive alloy rolled sheets; a highly anisotropic magnesium alloy (ZEK100) and two relatively isotropic dual phase steels (DP600 and DP780). The performance of the so-called butterfly type specimen (Mohr and Henn 2007, Dunand and Mohr 2011) was evaluated at quasi-static conditions along with the shear geometry of Peirs et al. (2012) using *in situ* 3-D digital image correlation (DIC) strain measurement techniques. It was shown that both test geometries resulted in similar trends of the load-displacement response; however, the fracture strains obtained using the butterfly specimen were lower for the ZEK100 and DP780. It was demonstrated that the ZEK100 exhibits strong anisotropy in terms of the shear work hardening rate and failure strain. Scanning electron microscope (SEM) images of the fracture surfaces revealed that both shear specimens led to a smooth fracture surface compared to the dimpled fracture surface obtained in uniaxial tension.

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INTRODUCTION

The development of stress state-dependent fracture surfaces and damage models to predict failure in automotive forming and crash simulations has created great interest in developing experimental tests to characterize failure under constant stress states [1,2]. The stress state is defined by the three invariants of the stress tensor that are commonly expressed in terms of the stress triaxiality and Lode parameter. The shear loading condition is critical to the development of the fracture surface since it corresponds to the origin of the surface with a stress triaxiality and Lode parameter of zero. Additionally, the shear stress response is important for the characterization of anisotropic materials and is not limited by the onset of necking as in a tensile test.

Typically, the shear response of ductile materials is determined by conducting torsion tests on thin walled tubular samples [3,4,5,6] but these tests are not suitable for sheet metals. Iosipescu [7] designed one of the first methods for the shear testing of sheet materials by using notched specimens subjected to four-point bending but now a simple shear test is the most common method. In this test, a rectangular specimen is mechanically clamped on two sides and a shear deformation is applied by moving the clamps parallel to each other in opposite directions. This test requires a special device that consists of two rigid parts with one piece remaining fixed and the other moving vertically or horizontally. The simple shear test and its extensions have been used to study the quasi-static [8,9,10,11] and

dynamic [12,13,14,15] behaviour of a large number of materials and have been reported to be an effective method for the testing of sheet specimens [10,16].

Alternatively, a number of experimental studies have involved designing complex test geometries with the aid of finite-element simulations where a tensile load is converted to a shear stress in the gauge area of the samples [17,18,19,20,21,22]. The principal advantage of these geometries is that the shear tests can be performed on conventional uniaxial tensile testing machines and be readily adapted to high strain rates or elevated temperatures. Recently, a new sample geometry for shear tests has been introduced by Peirs et al. [20] where a miniature shear sample has been used for both quasi-static and dynamic loading conditions. The design of this geometry is a modification of the geometries proposed by Tarigopula et al. [22] and Bao and Wierzbicki [23]. The advantage of this test geometry is that it has a relatively simple design and does not require through-thickness machining which may introduce surface defects. In Peirs et al. [20], the shear geometry was validated using a titanium alloy at quasi-static and elevated strain rates to determine the shear stress response. However, the geometry was not considered for fracture characterization or for a material that exhibits strong anisotropy. The aim of the present paper is to compare the geometry of Peirs et al. [20] with a modified version of the simple shear geometry using the so-called butterfly shear test [24,25]. Shear tests were performed on a highly anisotropic rolled magnesium alloy, ZEK100, and two relatively isotropic dual phase steels, DP600 and DP780. A 3-D digital image correlation (DIC) technique was used to obtain full-field strain measurements.

MATERIALS

Magnesium Alloy (ZEK100)

A rare-earth magnesium alloy sheet of ZEK100 (F-temper) with a nominal thickness of 1.55 mm was used in this study. The chemical composition of the alloy is presented in Table 1. Compared to the more common commercial AZ31B magnesium alloy, ZEK100 exhibits a relatively weaker basal texture that translates to higher ductility but a strong orientation dependency persists [26]. Uniaxial tensile tests were conducted under quasi-static conditions with samples extracted from the rolling, transverse and diagonal (45°) orientations of the sheet. The strong anisotropy of the ZEK100 is evident in Figure 1 as the initial yielding points, hardening rates, and maximum strains are dependent on the test orientation. The mechanical properties of the ZEK100 in uniaxial tension are presented in Table 2. This material also exhibits strong tension-compression asymmetry and compressive anisotropy [26].

Table 1. Chemical composition of ZEK100.

	Zn	Nd	Zr	Mn
Chemical composition (%wt)	1.3	0.2	0.25	0.01

Table 2. Mechanical properties of ZEK100 under tensile loading.

Tensile Loading Direction	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Total Elongation (%)
Rolling	206	243	26.3
Diagonal	143	225	45.6
Transverse	128	232	38.7

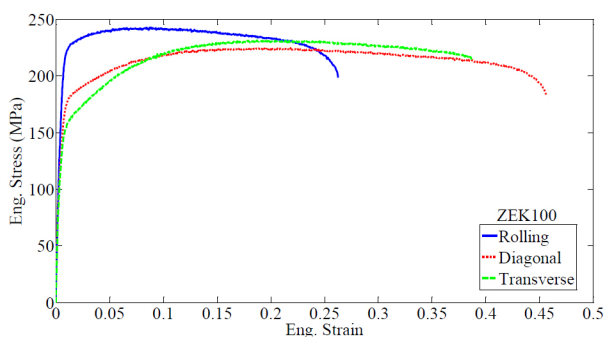


Figure 1. Engineering stress vs. engineering strain in uniaxial tension for ZEK100.

Dual Phase Steels

The commercial dual phase (DP) steels used in this study are DP600 and DP780, with a nominal thickness of 1.86 mm and 1.55 mm, respectively. Winkler et al. [27] have previously characterized the same materials used in this study and reported that the DP600 sheet contains approximately 5.5% martensite and 10% bainite with the balance being ferrite. Similarly, the DP780 contains 7% martensite and 30% bainite. Therefore, although these materials contain multiple phases, they are known as the dual phase steels. The DP780 is galvanized while the DP600 is uncoated. The response of the materials in uniaxial tension is shown in Figure 2 and the mechanical properties for both materials are presented in Table 3.

Table 3. Mechanical properties of the dual phase steels under tensile loading.

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Total Elongation (%)
DP600	403	644	25.4
DP780	525	806	21.6

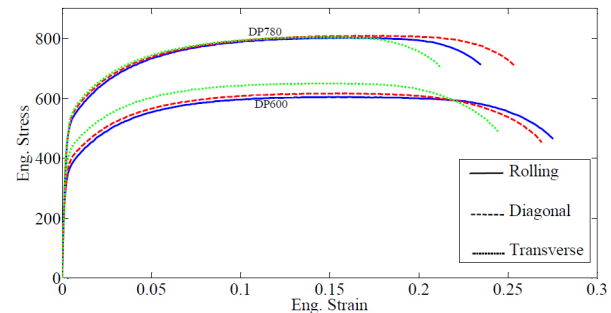


Figure 2. Engineering stress vs. engineering strain in uniaxial tension for the DP steels.

SHEAR TEST GEOMETRIES

Mini-Shear Specimen

The geometry of the shear sample developed by Peirs et al. [20] is shown in Figure 3. Due to the small size of the sample, throughout this paper, it will be referred to as the “mini-shear specimen”. The specimen geometry was designed so that the applied tensile load is converted to a shear stress in the gauge section of the specimen. The notches are offset by an eccentricity of 1 mm to provide a stress triaxiality very close to the theoretical value of zero for shear loading.

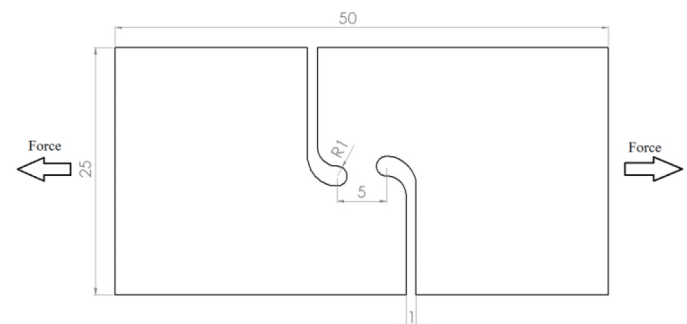


Figure 3. Mini-shear specimen geometry of Peirs et al. [20]. All dimensions are in millimeters.

This geometry has several advantages over its counterparts in the literature. Its small geometry makes it suitable for dynamic loading, and it has a rather simple geometry that is easy to fabricate. Contrary to most of the shear sample geometries in the literature [19,23,25], it does not have a reduced thickness in the shear zone which avoids complications such as machining-induced surface defects and residual stresses that can initiate fracture. For the DP steels the mini-shear specimens were manufactured with the applied shear load in the rolling direction. For the anisotropic ZEK100, shear samples were fabricated in the rolling, diagonal, and transverse directions (Figure 4). The tests were performed using a traditional tensile test machine with a cross-head velocity of 0.03 mm/s. The average shear

stress in the shear zone and the applied tensile force are directly related, and the average shear stress can be calculated by simply dividing the force by the shear area, as suggested by Peirs et al. [20]:

$$\tau_{avg} = \frac{F}{A_{shear}} = \frac{F}{Lt} \quad (1)$$

where τ_{avg} is the average shear stress, F is the force, t is the thickness, and L is the length of the shear region which is 3 mm. It will be shown in the following that the through-thickness strains are negligible in this test leading to a constant shear area; therefore, the average shear stress obtained with Eq. (1) can be considered as both the engineering and true stress since the gauge region is small and the shear strain distribution is relatively uniform.

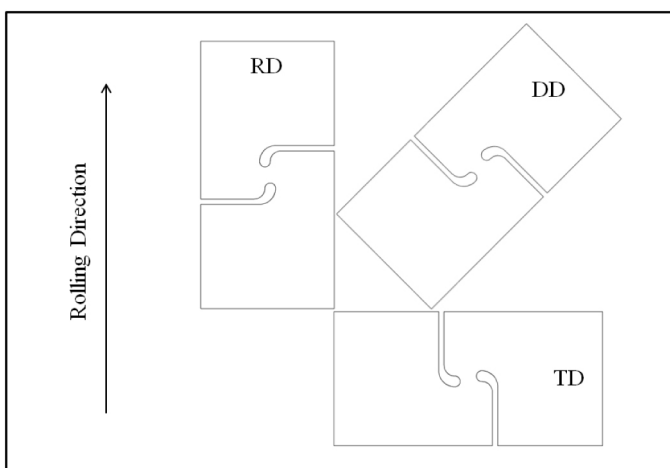


Figure 4. Schematic of the mini-shear specimen in different test orientations for ZEK100.

Butterfly Specimen

Figure 5 shows a schematic of the so-called butterfly test specimen adopted from Mohr and Henn [24] and Dunand and Mohr [25]. The specimen features a sharp reduction in thickness between the gauge section and the specimen shoulder. This versatile specimen was specifically designed to characterize fracture over a range of plane stress states in quasi-static conditions. The boundaries of the specimen are curved to avoid crack initiation at the gauge section boundaries.

The tests are performed using a custom-made testing device shown in Figure 6 which consists of a moveable and a fixed portion labeled as '1' and '2', respectively. The moveable portion slides vertically along a guidance rod; whereas the fixed portion is rigidly connected to the frame of the testing machine. Using this system, the loading condition can be controlled by the orientation of the specimen with respect to the vertical axis of the apparatus. The significant advantage of the butterfly test is that stress states from shear to plane strain can be obtained using only a single test geometry. However, as the focus of the present study is the shear loading condition, only the simple shear state is applied to the specimen. Similar to the mini-shear specimen, the butterfly samples were fabricated in the rolling direction for the DP steels and three orientations for the ZEK100, as shown in Figure 7. The thickness of the reduced section (t in Figure

5) was 0.95 mm for ZEK100, 0.90 mm for DP600, and 0.56 mm for DP780. Each of the butterfly specimens were manually sanded using 320 and 500 grit silicon carbide sandpaper to remove machining marks in the gauge region. The tests were conducted with a cross-head velocity of 0.025 mm/s.

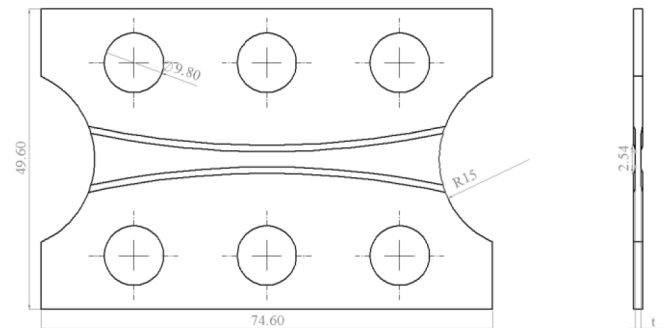


Figure 5. Butterfly specimen geometry. All dimensions are in millimeters.

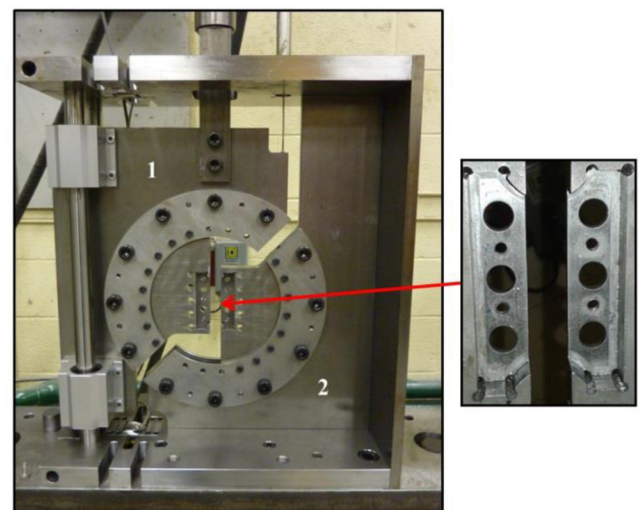


Figure 6. Testing device for the butterfly specimens.

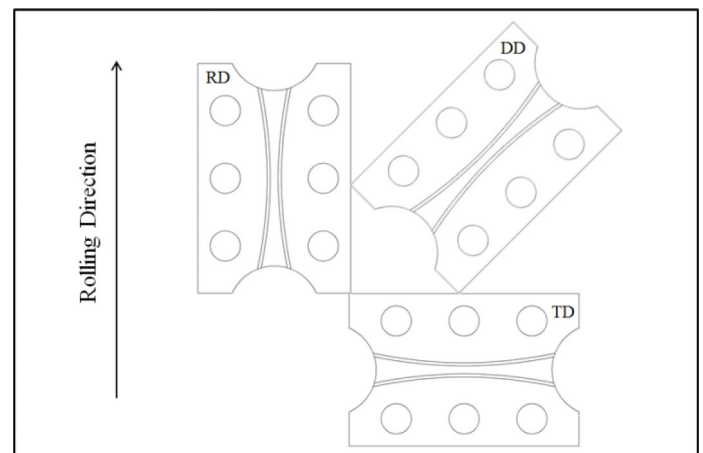


Figure 7. Schematic of the butterfly specimen in different test orientations for ZEK100.

Similar to the mini-shear sample, the shear stress in the butterfly specimen can be calculated using Eq. (1), where the load is divided by the cross section area. However, it will be shown in the following