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A grooved in-plane torsion test for the investigation of shear fracture in sheet materials

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ABSTRACT

The grooved in-plane torsion test is proposed as a shear fracture test for sheet materials. Unlike conventional simple shear tests, which are prone to incipient cracking at the free edges, this test uses radially continuous specimens, as firstly introduced by Marciniak and Kołodziejski (1972). In order to control the fracture position, a radial groove is cut out which allows to keep the fracture away from the clamping area. Thus, this test is able to create material fracture under ideal shear conditions i.e., the condition of vanishing triaxiality at the observable region of the test. Accordingly, the recent shear extended damage and fracture models for the selected material classes can be validated and/or quantified. With the help of finite element analysis (FEA), the corresponding fracture strains for the steel DP1000 were investigated using the proposed shear test and, additionally, three tensile tests conducted on notched specimens which cause fracture at moderate to high triaxialities. These are used to fit the fracture loci of some shear enhanced fracture criteria which have recently been proposed in the literature. The FEA shows that the proposed test provides fracture development under constantly zero triaxiality and zero Lode parameter conditions. Moreover, among the selected criteria, the model proposed by Lou et al. (2012) delivers the best results for selected experimental set. The developed test is ideally suitable for fracture parameter identification of sheet materials which do not show pronounced in-plane anisotropy, e.g. dual phase steels. Furthermore, this test is not limited to metallic materials.

1. Introduction

One main target of the numerical simulation of sheet metal forming processes it to assess the formability and fracture limits of the material during plastic deformation. Conventional forming limit diagrams fall short to predict shear failure at vanishing and low stress triaxialities (Li et al., 2010; Kim et al., 2011). Thus, there have been a growing interest in mathematical models capable of predicting shear fracture, see, e.g. Bao and Wierzbicki (2004), Xue and Wierzbicki (2008), Nahshon and Hutchinson (2008), Lou et al. (2012). Experiments, on the other hand, are equally important since validation of the mathematical models as well as the identification of the material parameters ultimately rely on the experiments.

The existing mechanical tests for shear fracture have some disadvantages, which are namely

- fracture occurence at the free edges due to inhomogeneous stress distribution, thus failing to achieve crack initiation under desired shear conditions
- varying triaxiality and Lode parameter during plastic deformation until crack

In the current study, a novel torsional test, the so-called grooved in-plane torsion test is presented, which was developed for the investigation of ductile failure of planar sheets. Unlike the original in-plane torsion test, grooved specimens free of slits are used. The aim is to achieve shear fracture in sheet materials supplying ideal shearing conditions of the material points at the fracture zone throughout the deformation history with vanishing instantaneous (and thus average) triaxiality, $\eta = 0$, and Lode parameter,[3] $\theta = 0$. This test is free of the mentioned edge effects. Due to the relatively simple specimen morphology, the test allows a direct determination

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[3] A detailed summary of these expressions are given on Section 3.1.

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of the equivalent strain at fracture from digital image correlation (DIC) results. Hence, an inverse analysis does not have to be involved in the parameter identification.

The outline of this paper is as follows. In Section 2, the current state of shear fracture testing for sheet materials is summarized. The theory behind certain fracture criteria, with emphasis on the shear enhanced ones with the selected notation for the characterization of the stress state at a material point, is given in Section 3. Section 4 presents the design of the test set up and specimen with numerical analyses justifying that the ideal conditions aimed at for a correct shear fracture test are met. Section 5 summarizes an attempt for a small parameter identification study for the listed fracture criteria, which is carried out by complementing the existing shear test with three additional tensile fracture tests on notched specimens for DP1000. Eventually, conclusions are drawn in Section 6.

2. Current state of shear fracture testing for sheet materials

Various shear tests for the characterization of plastic material behavior of sheet metals are known in literature, however, not all are suitable for the identification of shear fracture. In Table 1, an overview of available shear test approaches is given with corresponding references and comments on the test characteristics and purposes. Two main aims exist when performing a shear test: the characterization of plastic hardening (e.g. determination of the flow curve, identification and partition of isotropic and kinematic hardening) and the characterization of formability and fracture behavior.

2.1. Shear and torsion tests for characterization of plastic hardening

Fig. 1 shows five specimen approaches for the determination of the flow curve in shear tests. One can distinguish between translational and rotational fixture movements. Typical shear test kinematics is achieved by a parallel displacement of two opposing edges in opposite directions. In numerous publications, like Hu et al. (1992), this principle is followed by testing a single sided shear specimen (see Fig. 1(b)). Basically with the same kinematics but with two symmetrical shear zones, a specimen design by Miyauchi (1984) was suggested in order to avoid the unwanted reaction moment on the fixtures (Fig. 1(a)). The ASTM B831 Standard suggests a much simpler clamping configuration by using the kinematics of tensile tests. The complexity is moved to the specimen design, involving diagonal cuts in the specimen (see Fig. 1(c)). The advantage is the compatibility of this specimen with testing devices designed for tensile tests. However, the shear zone may rotate during deformation. Merklein and Biasutti (2011) presented a modified version of this specimen with additional supporting fixtures in order to stiffen the regions without plastic deformation as well as to allow cyclic loadings.

Torsion tests for sheet materials are still rarely applied. The initial work for the in-plane torsion test was done by Marciniak (1961), who proposed this test in order to investigate cyclic hardening of copper. A round sheet specimen is clamped concentrically in the center and at the outer rim and torsioned in the sheet plane. Shear deformation is created in the free ring-shaped area between the clamps. Further developments by Tekkaya et al. (1982) allow the usage of the in-plane torsion test for the flow curve determination. The in-plane torsion test is free of edge effects due to the absence of any edges. Thus, a high deformation can be achieved. Recent developments suggest applying optical strain measurements in this test Yin et al. (2011). Brosius et al. (2011) proposed a modification of the torsion specimen, the so called “twin bridge shear test”, with round slits in order to obtain a shear test with specific orientation to the rolling direction. Yin et al. (2014) showed that this specimen modification produces results which are comparable to the Miyauchi specimen and the shear test according to ASTM B831.

2.2. Shear tests for fracture and formability testing of sheets

As the above described approaches are originally designed for the determination of plastic hardening, they are not generally suitable for the characterization of formability limits by fracture. The shear tests and the twin bridge specimen are affected by edge effects which are explained in Section 1. Moreover, inhomogeneous stress and strain distributions within these tests lead to stress states which deviate significantly from the simple shear state, especially at both ends of the shear zone. For flow curve determination, the influence of this effect can be reduced by increasing the ratio of length to width. Bouvier et al. (2006) suggested a proportion of 10:1. The position of the incipient fracture is very important for the fracture analysis. For the mentioned shear tests, which involve discontinuities at the sheared stress carrying zone, the crack tends to emanate at the edges where the tensile stress state is dominant. Hence, the material failure under shear conditions cannot be guaranteed. Obviously, the stress states at the crack tip process zone for a propagating crack has additional complexities. This drawback of edge effects does not exist for the in-plane torsion test without slits. The application of this test for formability testing is shown by Marciniak and Kołodziejski (1972), where failure occurs at the inner clamping. However, the shear stress state overlaps with the clamping pressure at this position.

Hence, the main challenge for the experimental characterization of sheet metal failure under simple shear loading is avoiding the crack initiation at free edges, while maintaining a desired and constant stress triaxility and Lode parameter for simple shear. Fig. 2 shows schematically four examples of specimen designs which were originally developed with this intention. An early approach with notched bars was suggested by Iosipescu (1967) (Fig. 2(a)). A modified version of this specimen is standardized as

Table 1
Shear tests for sheet materials.

Publications	Loading	Characteristics	Purpose
Miyauchi (1984)	Translational	Planar shear test with two symmetrical zones	Plastic hardening
Hu et al. (1992), Rauch (1998) and Bouvier et al. (2006)	Translational	Planar shear test with one single shear zone	
ASTM B831, Merklein and Biasutti (2011)	Translational	Planar shear test with slits suitable for tensile test kinematics	
Tekkaya et al. (1982)	Torsional	In-plane torsion to reach high strains	
Brosius et al. (2011) and Yin et al. (2012)	Torsional	Modified in-plane torsion test with slits	
Bao and Wierzbicki (2004) and Mohr and Henn (2007)	Translational	Grooved shear specimen geometry (Butterfly)	Formability, fracture
Shouler and Allwood (2010)	Translational	Shear specimen with slits for tensile loading	
Iosipescu (1967), ASTM D5379	Translational	Shearing of notched bars	
Marciniak and Kołodziejski (1972)	Torsional	In-plane torsion test	