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Failure characteristics of a dual-phase steel sheet

Oscar Björklund*, Larsgunnar Nilsson

Division of Solid Mechanics, Linköpings University, SE-581 83 Linköping, Sweden

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ABSTRACT

Failure in ductile sheet metal structures is usually caused by one, or a combination of, ductile tensile fractures, ductile shear fractures or localised instability. In this paper the failure characteristics of the high strength steel Docol 600DP are explored. The study includes both experimental and numerical sections. In the experimental sections, the fracture surface of the sheet subjected to Nakajima tests is studied under the microscope with the aim of finding which failure mechanism causes the fracture. In the numerical sections, finite element (FE) simulations have been conducted using solid elements. From these simulations, local stresses and strains have been extracted and analysed with the aim of identifying the fracture dependency of the stress triaxiality and Lode parameter.

1. Introduction

It is important to understand the failure process in high-strength sheet metals in order to predict their mechanical responses using finite element (FE) simulations. Teirlinck et al. (1988) describes four failure phenomena observed in uniaxial tension specimens: plastic failure, ductile fracture, shear fracture, and cleavage and brittle intergranular fracture. It should be noted that failure due to cleavage and brittle intergranular fracture, is considered as a brittle fracture which not will be covered here. Failure is defined as the local loss of load-carrying capacity, while fracture is defined as material separation. Consequently, failure incorporates the term fracture but may also be caused by other phenomena which do not include material separation e.g. material and geometrical instabilities.

The term plastic failure used in Teirlinck et al. (1988), is often generalised to represent any sheet instability, cf. Lademo et al. (2009). All fractures in ductile sheet metals are considered to be ductile. Therefore, the notation ductile tensile fracture and ductile shear fracture have been introduced in this study. Ductile fracture is, from this point, used both for the ductile tensile and the ductile shear fracture. The ductile fracture process is characterised by initiation, growth and coalescence of voids in the material, the loaded area is reduced, and eventually material fracture occurs. The fracture surface is characterised by the presence of dimples. The shape of these dimples is influenced by the direction of the deformation. In a tensile fracture, dimples usually have a circular appearance while in a shear dominated fracture the dimples have an elongated elliptical shape, see Metals Handbook (1974). Furthermore, the ductile shear fracture surface consists of fine, closely-spaced dimples which are much wider than they are deep, see Garrison and Moody (1987). Weck and Wilkinson (2008) studied the fracture characteristics of specimens with laser-drilled holes in different orientations. They concluded that when the holes are located parallel to the loading direction, coalescence occurred by internal necking of the ligaments between the holes. However, when the holes are oriented at an inclined direction to the loading direction, coalescence occurred by a shearing process. Ductile shear fracture can be caused either by extensive slip on the activated slip planes, see Dieter (1986), or as a result of void nucleation in slip bands. Both these mechanisms are favoured by shear stresses. When voids nucleate in slip bands, the loaded area is reduced such that plastic flow localises there. Continued shear increases the area of voids until separation occurs. Furthermore, as stated by Teirlinck et al. (1988) "Voids which extend in shear need not increase in volume, so shear fracture is less pressure-dependent than ductile fracture, though it remains more pressure-dependent than purely-plastic failure". The ductile shear fracture can be either a through-thickness shear fracture, see e.g. Björklund et al. (2013), or an in-plane shear fracture, see e.g. Li et al. (2010). Instabilities arise when the strain hardening can no longer compensate for the reduction in load carrying area. Hence, strain localises at a small region and the material fails due to ductile tensile or ductile shear fracture. By examining the fracture surface under a microscope, it is most often noted that different fracture types are present in different areas of the specimen, cf. Li et al. (2011). For example, in the

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* Corresponding author. Tel.: +46 13281111; fax: +46 13282717.
E-mail address: oscar.bjorklund@liu.se (O. Björklund).

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tensile test of a round specimen the failure process is initiated by an instability followed by a ductile tensile fracture in the centre of the specimen before finally complete separation occurs by shear, cf. Hosford (2005).

Numerical studies of the deformation of cylindrical voids by e.g. McClintock (1968) and spherical voids by e.g. Rice and Tracey (1969) have shown that the growth-rate depends on the stress state, and in particular the stress triaxiality. Furthermore, as stated in Lemaitre and Chaboche (1990), the nucleation and growth of voids in isotropic material depends not only on the first two stress invariants, as expressed by the stress triaxiality, but also on the third stress invariant. The dependency on the third stress invariant has been shown numerically by, for example, Zhang et al. (2001). This was achieved by using the Lode parameter, see Lode (1926), which incorporates the third stress invariant. Subsequently the influence of both the stress triaxiality and the Lode parameter has been studied numerically, e.g. Barsoum and Faleskog (2007a) and experimentally, e.g. Barsoum and Faleskog (2007b).

The reduction in load-carrying area due to void growth and coalescence leads to material softening. In damage models, material softening is coupled to the constitutive relation either by a porous plasticity, cf. Gurson (1977), or by continuum damage mechanics, cf. Lemaitre (1985). In most fracture criteria, on the other hand, the softening effect is not included in the constitutive relation. Several phenomenological criteria have been proposed for predicting ductile fracture. The Cockroft and Latham (1968) criterion is a modified maximum plastic work criterion based on the maximum principal stress. Johnson and Cook (1985) developed a criterion that depends on stress triaxiality, strain rate, temperature and equivalent plastic strain. Bai and Wierzbicki (2010) introduced a ductile fracture criterion based on a modification of the Mohr–Coulomb criterion, henceforth denoted as the MMC criterion. In the criterion presented by Aretz et al. (2011), a loading mode parameter was introduced that classifies the stress state from pure tensile to pure compression. Gruben et al. (2012) presented an extension of the Cockroft–Latham criterion incorporating both the maximum principal stress and the maximum shear stress. Lou et al. (2012) presented another fracture criterion, which combines the effect of stress triaxiality and maximum shear stress. Lou and Huh (2013a) reformulated this criterion to incorporate Lode parameter dependency.

Prediction of sheet instability due to localisation has been studied by the use of analytical models for the negative side of the forming limit diagram (FLD), see Hill (1952), and for the positive side of the FLD, see Swift (1952). Hora et al. (1996) presented a more general analytical instability model which is valid both in the positive and negative domains of the FLD. For a recent review on sheet instability, see Aretz (2004). Also instability criteria based on non-homogeneous sheets have been used to predict localisation, see Marciniak and Kuczynski (1967). Detailed finite element (FE) models with elasto-plastic or elasto-viscoplastic constitutive laws can be used to capture instability phenomena in details, cf. Lademo et al. (2004).

As an alternative to the phenomenological models used to predict fracture and instabilities, the experimental forming limit curve (FLC) has been a popular mean. However, the FLC is a useful locus of failure only for proportional strain paths since the FLC depends on the strain history, cf. Hosford and Cadell (1993). In order to address the problem of path dependency in strain-based FLDs, stress-based FLDs have been proposed, see e.g. Stoughton (2000). The stress-based FLDs have been argued to be independent of the strain path. One problem with the stress-based FLCs is the reduction of hardening, which causes a considerable change in strain close to necking. This effect makes it hard to visualise the margin of safety in the stress diagram. A cure for this is to visualise the FLC in a diagram of the effective plastic strain which is directly linked to the stress by the hardening curve, see e.g. Stoughton and Yoon (2012).

Failure and fracture of metals have been studied extensively. A review of some frequently used fracture criteria and the issue of how to calibrate them was presented by Wierzbicki et al. (2005). Pedersen et al. (2008) studied the formability of AlMgSi alloys with different grain structures under linear loading paths. Lademo et al. (2009) predicted fracture in an aluminium alloy subjected to the Nakajima tests by use of Cockroft-Latham fracture criterion combined with an FE-based prediction of instabilities. Mirone and Corallo (2010) used the maximum shear stress criterion, the Bao and Wierzbicki (2004) criterion and an evolution of the later criterion by Wierzbicki et al. (2005) to study the influence of both the stress triaxiality and the Lode parameter on fracture in four different metals. Luo and Wierzbicki (2010) predict shear fracture during the stretch-bending of dual-phase steel using the MMC criterion. The special case of shear fracture, due to the high-curvature die radii, in sheet forming operations of three dual-phase steels was studied by Kim et al. (2011). Dunand and Mohr (2011) compared a shear modified Gurson criterion by Nielsen and Tvergaard (2009), and the MMC criterion in predictions of fracture over wide range of stress states for a TRIP780 steel. Stoughton and Yoon (2011) predicted fracture during opening of a food-can using a plane stress assumption and the maximum shear stress criterion. Gruben et al. (2011) studied the fracture characteristics of a cold-rolled dual-phase steel using FE simulations and digital image correlation (DIC). In Gruben et al. (2013) DIC was used to identify the onset of instability and fracture in both Marciniak–Kuczynski and Nakajima tests of a cold-rolled dual-phase steel. Ebnoether and Mohr (2013) studied the fracture of low carbon steel sheets using the original Mohr–Coulomb criterion and the MMC. Aretz et al. (2013) predicted fracture during the forming of an AA 5182 aluminium alloy.

In this paper the fracture of Docol 600DP, a dual phase high strength steel, is studied. The major objective of this study is to identify the fracture that occurs in Nakajima tests designed for different straining situations. An extensive test programme has been carried out, which is presented in Section 2. The different failures are observed in microscope as reported in Section 2.1. A brief discussion of the constitutive equation utilised follows in Section 3, and an identification of key parameters for failure representation is given in Section 4. The numerical simulations are briefly described in Section 5 followed by a validation of the simulation models. Finally, findings and results are discussed in Section 7.

2. Experimental work

The high strength steel (HSS) Docol 600DP is a dual phase steel consisting of about 75% ferrite and 25% martensite, in which the microstructure is produced by heat treatment, see Olsson et al. (2006). The nominal thickness of the steel sheets studied here was 1.48 mm with a standard deviation measured to be 5.0 μm. Tensile, plane strain (notched tensile test) and in-plane shear tests, with geometries according to Fig. 1, were performed in an INSTRON 5582 testing machine with a 100 kN load cell. The loading velocity has been selected such that a quasi-static loading condition is obtained, i.e. a strain rate of approximately $10^{-4}\,\mathrm{s}^{-1}$. A representative fracture for each specimen type can be seen in Fig. 2. Both the tensile and plane strain specimens fractured after maximum load and the fracture is initiated at the specimen centre, see Fig. 3. Regarding the shear specimen the maximum load occurs just before a complete material separation and it is hard to identify the location of the fracture initiation. In Björklund et al. (2013) the fracture was assumed to start at the edge of the specimen, since the maximum value of the fracture parameter according to Cockroft and Latham