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Predicting instability at die radii in advanced high strength steels

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ABSTRACT

Recently, the automotive industry has seen increased use of advanced high strength steels (AHSS) due to superior combinations of strength, ductility, and weldability. However, during stamping of AHSS; fractures are periodically observed along bends of small radii. These fractures have been termed 'shear fractures' due to limited localized necking, and fracture on alternating 45° planes, through thickness. Such fractures have proven difficult to predict using traditional measures of formability, such as the forming limit diagram (FLD). The present study outlines an approach to predict shear fractures by instability at die radii, represented by maximum applied tensile force as a function of die radius. Due to a transition from die instability to tensile instability with increasing die radius, material tensile strength is imposed as a limiting condition at large radii. Promising correlations are observed for a wide range of commercially produced AHSS including HSLA450, DP600, TRIP780, DP780, and DP980. Both experimental results and theory suggest a critical radius (normalized by sheet thickness: R/t_{crit}), above which materials will fail in tension, independent of die radius, and correspondingly localized shear fracture would not occur. The critical R/t value is a measure of formability, since for lower R/t_{crit} values there is a greater range over which materials exhibit tensile failure, readily predicted by material tensile strength. For the steels analyzed in this study, critical R/t values were found to be dependent primarily on material tensile strength, and to a lesser extent, material yield strength, strain hardening exponent (n value), and instability strain.

1. Introduction

Use of advanced high strength steels (AHSS) has been increasing in recent years due to superior mechanical properties and increased demand for crashworthiness and mass avoidance in the automotive industry. These steels are often multiphase materials, such as dual phase (DP), transformation induced plasticity (TRIP), and complex phase (CP) with tensile strengths of 600 MPa and higher. While tensile strengths are continually pushed to higher levels, formability is compromised, as demonstrated by shear fractures that periodically occur at tight bending radii during industrial stamping trials. Shear fractures run parallel to die radii, exhibit minimal localized necking, and fracture on alternating 45° planes through thickness. Sriram et al. (2003) have shown that traditional formability measures, such as the forming limit diagram (FLD), are insufficient in predicting such failures.

Recently, a significant effort has been made in the metal forming community to address the issue of shear failures in bending. Bai and Wierzbicki (2008) have developed an analytical methodology and ductile fracture criterion which attempts to predict failure location and mode (shear failure at die or tensile failure in free span). Although promising correlations to selected stamping trials have been observed, more systematic experimental evidence is needed. Kim et al. (2009) have suggested thermal build up during draw bend testing has significant influence in fracture due to material softening. Although little has been published to date, modeling appears to predict laboratory results well for select materials. In other works, Levy and Van Tyne (2009) have shown a linear relationship between the normalized failure stress and the sheet thickness to die radius ratio. However, these linear relationships are empirically derived and are unique to particular steel grades. Yet others are approaching the problem from a micromechanical perspective, using finite element (FE) packages to model stress and strain partitioning within a steel microstructure (Krempaszky et al., 2007). However, as with much FE modeling work, failure can be difficult to predict. Lastly, Han and Kim (2003) have shown ductile fracture limits in sheet metal forming of high strength steels to be controlled by strain localization, (e.g. localized necking). Although the aforementioned research groups have very different approaches, the root cause, or causes of shear failures are still unknown. Additionally, with the introduction of high strength materials and complex microstructures, a reinvestigation of formability is required.

The aim of the present work is to develop an instability analysis with which shear fractures can be anticipated using stamping parameters such as sheet thickness and bend radii and material properties such as yield strength, elongation and n value. An insta-

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Table 1
Experimental material designations, thicknesses and compositions (wt. pct.). Martensite volume fractions (MVF) are included for the dual phase steels calculated using ASTM E-562-02.

Type	Thickness (mm)	MVF (%)	C	Mn	Si	Cr	Mo	Ti	Al
HSLA450	1.4	–	0.10	1.34	0.01	0.04	0.00	0.00	0.05
DP600	1.0	20.2	0.09	1.66	0.01	0.19	0.19	0.00	0.06
DP600	1.4	22.4	0.08	1.81	0.01	0.18	0.18	0.00	0.04
TRIP780	1.0	–	0.14	2.26	0.07	0.09	0.09	0.01	1.84
DP780	1.0	27.0	0.14	1.95	0.02	0.24	0.17	0.00	0.07
DP980	1.4	49.6	0.15	1.87	0.02	0.17	0.32	0.00	0.06

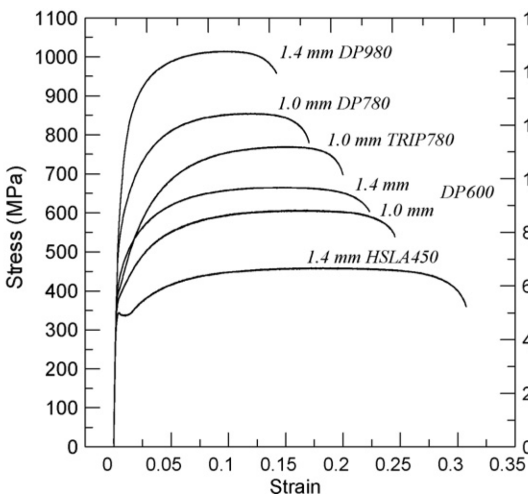

Fig. 1. Engineering stress–strain curves for the six experimental steels. A wide range of elongations and tensile strength levels are observed.

bility condition is applied in the present analysis which predicts the onset of localized necking at the sheet–die interface. Data from a previously performed study (Hudgins et al., 2007) which included six steels tested in bending under tension were used to validate theoretical predictions.

2. Materials

Table 1 summarizes the six commercially produced steels used for this study, an HSLA450, two DP600 materials, a DP780, a TRIP780, and a DP980. Materials were chosen to represent industrially relevant AHSS spanning a range of microstructures, strength levels, elongation values, and thicknesses. Included in Table 1 are calculated martensite volume fractions (MVF) for all DP steels (Hudgins et al., 2007). The three strength levels of the DP steels provide the opportunity to compare UTS, likely governed by MVF, within a particular microstructure. The two DP600 materials allowed for a comparison of thickness effects given a fixed microstructure, and the TRIP steel provides a comparison of work hardening behavior at a similar strength level (when compared to the DP780). The HSLA is representative of a conventional ferrite based high strength sheet steel, which can be contrasted with the other multiphase AHSS materials in the study. Table 1 also shows that generally the higher the targeted strength level, the greater the amount of hardenability elements in the alloy. The DP980 contains significantly greater amounts of molybdenum when compared to the lower strength DP steels. Additionally, the carbon content increases with targeted strength level (last three numbers in the steel designation, in MPa). All materials were galvannealed coated and tested without removal of the coating.

ASTM E-8 tensile specimens, machined parallel to the rolling direction, revealed typical flow behavior for each microstructure, as shown in Fig. 1. DP steels exhibited continuous yielding, with comparatively low yield to tensile strength levels, while the TRIP steel showed a large amount of strain hardening and a relatively low yield strength. The HSLA material showed a small amount of yield point elongation and little strain hardening.

Table 2 summarizes the tensile properties which are the average of three repeated tests. Excellent consistency was found between tests. A crosshead displacement rate of 2.54 mm/min was used for all tensile testing, as both literature and selected trials indicate little strain rate sensitivity at rates below 0.1 s^{-1} (Clarke et al., 2003). Uniform elongation values were determined by applying the definition of diffuse necking: equating instantaneous n value to true strain. Nearly all materials met the intended strength level, with the exception of TRIP780, which showed a peak stress of 770 MPa. The effect of increasing MVF in the dual phase grades is shown to increase the tensile strength level from 607 to 1014 MPa (for materials exhibiting 20.2% and 49.6% martensite, respectively). As expected, uniform elongation values decreased continuously with increasing MVF in the DP steels. The TRIP steel showed ductility values similar to the DP600 materials.

3. Experimental procedure

Although originally used by Vallance and Matlock (1992) for tribology studies, the bending under tension test has since been modified to accurately reproduce shear failures observed in industry (Hudgins et al., 2007). As shown in Fig. 2, the test involves two independently controlled hydraulic actuators, oriented 90° from one another and separated by a fixed (non-rotating) cylindrical roller, which acts as a die. Dies of different radii can be used, altering the stress state experienced by the sheet. Small die radii promote shear type failures at the die location, while large radii have little effect on fracture, and sheets fail in tension in the free span of the sheet.

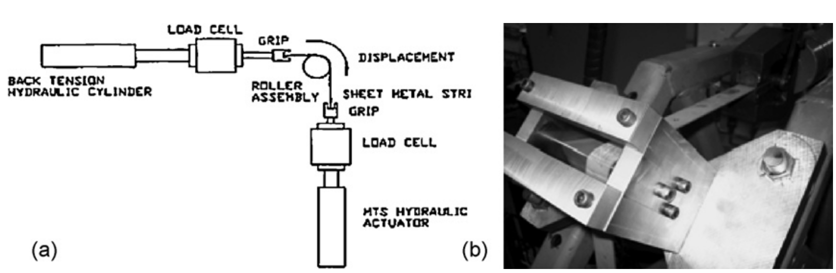

Fig. 2. The bending under tension test, shown by (a) schematic drawing of a commercial test frame and (b) experimental setup.