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Influence of stress triaxiality and strain rate on the failure behavior of a dual-phase DP780 steel

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ABSTRACT

To better understand the in-service mechanical behavior of advanced high-strength steels, the influence of stress triaxiality and strain rate on the failure behavior of a dual-phase (DP) 780 steel sheet was investigated. Three flat, notched mini-tensile geometries with varying notch severities and initial stress triaxialities of 0.36, 0.45, and 0.74 were considered in the experiments. Miniature specimens were adopted to facilitate high strain rate testing in addition to quasi-static experiments. Tensile tests were conducted at strain rates of 0.001, 0.01, 0.1, 1, 10, and 100 s^{-1} for all three notched geometries and compared to mini-tensile uniaxial samples. Additional tests at a strain rate of 1500 s^{-1} were performed using a tensile split Hopkinson bar apparatus. The results showed that the stress–strain response of the DP780 steel exhibited mainly positive strain rate sensitivity for all geometries, with mild negative strain rate sensitivity up to 0.1 s^{-1} for the uniaxial specimens. The strain at failure was observed to decrease with strain rate at low strain rates of 0.001–0.1 s^{-1}; however, it increased by 26% for an increase in strain rate from 0.1 to 1500 s^{-1} for the uniaxial condition. Initial triaxiality was found to have a significant negative impact on true failure strain with a decrease of 32% at the highest triaxiality compared to the uniaxial condition at a strain rate of 0.001 s^{-1}. High resolution scanning electron microscopy images of the failure surfaces revealed a dimpled surface while optical micrographs revealed shearing through the thickness indicating failure occurred via ductile-shear. Finite element simulations of the tests were used to predict the effective plastic strain versus triaxiality history within the deforming specimens. These predictions were combined with the measured conditions at the onset of failure in order to construct limit strain versus triaxiality failure criteria.

1. Introduction

Increasingly stringent automotive fuel economy and greenhouse gas emission standards are forcing automotive manufacturers to reduce the weight of their fleets while maintaining or improving crashworthiness and occupant safety. Large contributors to vehicle mass are the chassis and body structure, both of which are typically fabricated from low strength steel. Substitution of high strength steels into these components permits thinner sections, ultimately leading to reduced mass. However, the performance of these alloys must be investigated to support simulations of their formability during manufacturing and in-service performance (crashworthiness), such as the work by Abedrabbo et al. [1,2] who considered the alloy examined in this paper subjected to axial crush loading. Among other important findings, Abeddrabo et al. [1,2] found that dual phase (DP) 780 steel offered considerably higher energy absorption compared to drawing quality and high strength low alloy (HSLA) steels; however, their work did not consider the potential onset of fracture during axial crush deformation which can be important in higher strength materials.

Several publications [3–5] have investigated the uniaxial stress–strain behavior of DP780 steel sheet subjected to a variety of strain rates. Huh et al. [3] tested 1.0 mm sheet at strain rates between 0.001 s^{-1} and 100 s^{-1}. The results showed a reduction in elongation up to a strain rate of 0.01 s^{-1} followed by increased elongation up to 100 s^{-1}. Minimal increases in strength were observed from 0.001 to 0.1 s^{-1}; however, strength was shown to increase from 0.1 to 100 s^{-1}. Kim et al. [4] tested 1.4 mm sheet at a quasi-static strain rate of 0.001 s^{-1} and elevated strain rates between 0.1 s^{-1} and 200 s^{-1} and demonstrated a reduction in true failure strain up to 1 s^{-1}, increasing failure strains up to 10 s^{-1}, and

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decreasing again up to 200 s^{-1}. An increase in strength was also observed from a strain rate of 0.1–100 s^{-1}. Winkler et al. [5] tested 1.56 mm sheet at strain rates between 0.001 and 1 s^{-1} and additionally at 1500 s^{-1} and showed a reduction in true failure strain and strength up to a strain rate of 0.1 s^{-1} and increases in both as strain rate increased to 1500 s^{-1}. These three works show similar trends in true failure strain and strength; however, only Kim et al. demonstrated a reduction in true failure strain between 10 s^{-1} and 100 s^{-1}. Only Winkler et al. performed tests at 1500 s^{-1}.

The effect of stress triaxiality on the ductility of metals has been well documented since the early work of Bridgman [6], McClintock [7], Rice and Tracey [8], Mackenzie et al. [9], and Hancock and Mackenzie [10]. Much of this pioneering work was focused on smooth and pre-notched axisymmetric round bars, flat specimens, and flat, grooved plates. Recently, there have been many experimental studies on the effects of stress triaxiality on the failure behavior of aluminum [11–13], iron [13], structural steel [14,15], pipeline steel [16], and mild steel [13,17,18]. Results of these studies were consistent with earlier findings and showed that increased stress triaxiality resulted in a reduction in ductility. It was noted by Mirza and Barton [13] that increases in stress triaxiality had a larger effect on steel compared to aluminum. Although some of these works [13–15,17] performed tests at elevated strain rates up to 10,000 s^{-1}, only Mirza and Barton [13] found a transition from ductile to brittle fracture that was dependent on both strain rate and stress triaxiality for mild steel.

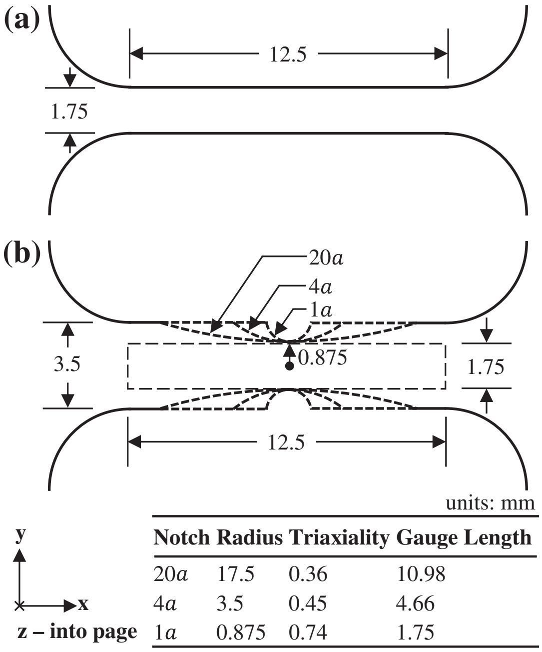
The purpose of the current work is to investigate the failure response of an advanced high strength steel alloy, DP780, to varying stress states and strain rates. Although previous work, as cited above, has investigated the role of strain rate on the failure response of DP780 steel under uniaxial conditions, a review of the current literature has not identified currently published work addressing the combined effect of triaxiality and strain rate on the failure response of DP780 steel sheet. A better understanding of this failure behavior may be a significant contributor to improved predictions of in-service performance and crash response. To this end, one uniaxial and three flat, notched DP780 steel specimen geometries have been tested at seven strain rates to characterize the stress–strain response and the limit strains as a function of triaxiality and strain rate. Finite element analysis of the tests was performed to determine the evolution of effective plastic strain and triaxiality during deformation. Additionally, scanning electron microscopy (SEM) images and optical micrographs were used to correlate the observed stress–strain response to the microstructure.

2. Experimental procedures

1.56 mm DP780 cold-rolled hot-dip galvanized sheet manufactured by Dofasco Inc. was used in this investigation. Fig. 1 shows the geometry of the uniaxial and flat, notched mini-tensile samples as well as the axis orientations adopted for the present work. The mini-tensile uniaxial samples were developed by Smerd et al. [19] for high strain rate testing and were shown to provide uniaxial constitutive data with a stress–strain response that is in agreement with standard 50 mm ASTM: E8/E8M samples prior to the onset of necking.

In order to obtain a range of initial stress triaxialities for this study, several flat, notched tensile samples were designed based on the approximation proposed by Bridgman [6]. In his work, Bridgman proposed the following corrections to the state of stress in a flat (plane strain) specimen undergoing necking:

$$\sigma_x = \bar{\sigma} \ln\left[1 + \frac{a}{2R}\left(1 - \frac{y^2}{a^2}\right)\right], \tag{1}$$



Notch	Radius	Triaxiality	Gauge Length
20a	17.5	0.36	10.98
4a	3.5	0.45	4.66
1a	0.875	0.74	1.75

Fig. 1. Schematic of mini-tensile specimens. (a) Uniaxial sample, and (b) flat, notched sample.

$$\sigma_y = \bar{\sigma} \ln\left[1 + \frac{a}{2R}\left(1 - \frac{y^2}{a^2}\right)\right], \tag{2}$$

$$\sigma_z = \bar{\sigma}\left[1 + \ln\left[1 + \frac{a}{2R}\left(1 - \frac{y^2}{a^2}\right)\right]\right], \tag{3}$$

where $\sigma_{x,y,z}$ are the three principal stress components, $\bar{\sigma}$ is the effective stress, R is the radius of curvature due to deformation or pre-notching, and a is half the ligament width, where the ligament width is the distance between the notches and is equivalent to the gauge width of the uniaxial specimens (1.75 mm in this work). Varying y permits the stress calculations along the width of the specimen. Eqs. (1)–(3) can be combined to determine the mean stress, σ_m, and subsequently the stress triaxiality, η:

$$\sigma_m = \frac{1}{3}(\sigma_x + \sigma_y + \sigma_z), \tag{4}$$

$$\eta = \frac{\sigma_m}{\bar{\sigma}}. \tag{5}$$

Therefore, the triaxiality along the width of a flat specimen is found from:

$$\eta = \frac{1}{3} + \ln\left[1 + \frac{a}{2R}\left(1 - \frac{y^2}{a^2}\right)\right]. \tag{6}$$

At the centre of the specimen this reduces to the familiar form of:

$$\eta = \frac{1}{3} + \ln\left(1 + \frac{a}{2R}\right), \tag{7}$$

which is identical to that found for axisymmetric specimens.

The analytical triaxialities reported herein when discussing the measured data were found from Eq. (7) and are referred to as *initial* since triaxiality evolves with deformation and varies throughout the specimen. During deformation the radius of the notch and the ligament width will change and the sheet material will neck through the thickness affecting the triaxial state of the specimen. Moreover, Bridgman assumed constant effective strain across the specimen, which may not be accurate. Therefore, this evolution of the triaxiality and effective strain will be presented and