Strain Rate and Orientation Effects on Fracture Strain Limits in Advanced High Strength Steel

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Abstract. There is increasing interest in establishing fracture limits for advanced high strength steels where there is significant likelihood of fracture intervening during crash of structural components. Fracture strain data obtained from quasi-static tensile tests conducted at $10^{-3}$/s are commonly extended to predict crash events in design. In this study, true fracture strain measurements based on DIC as well as microscopy are presented for several high strength steels with ultimate tensile strength ranging from 1000-1200 MPa under uniaxial tension conditions over a range of strain rates from $10^{-3}$/s to $10^{-1}$/s and in different sheet orientations. Implications of orientation and strain rate effects on fracture strain will be discussed in the context of local versus global formability considerations used in material selection as well as usage of fracture strain data in crash simulation.

1. Introduction

The rapid introduction of greater than 1 GPa steels in automotive structural components has heightened the need to better understand fracture behavior and to establish fracture limit strains to support simulation efforts. The fracture mode at room temperature quasi-static conditions in the majority of dual-phase and multiphase steels (that include retained austenite besides ferrite and martensite in the structure) is ductile fracture. The subject of ductile fracture has been well studied and is generally understood as a process involving void nucleation, growth and coalescence \cite{1, 2}. Several ductile fracture models have been developed either based on explicit incorporation of micromechanics associated with void growth \cite{2-5} or using non-associated fracture models \cite{6-8}. The generalization of the Mohr Coulomb model by Bai and Wierzbicki \cite{8} into the space of equivalent plastic strain, stress triaxiality and Lode angle commonly referred to as the MMC model is finding wide use in the automotive industry to predict the occurrence of fracture limits in different stress states. It is also noted that in finite element simulations, it is typical to use a regularization scheme that scales the fracture limit strain with element size used in the model \cite{9}. True fracture strain data is also of interest in the context of using local versus global formability considerations to support material selection for applicability of different grades in automotive structural applications \cite{10}.

The objective of the present work is to experimentally determine fracture limits for several advanced high strength steels including dual phase and multiphase steels as a function of sample orientation and strain rate. Physical measurement of fracture strains is presented along with digital image correlation based measurement on the frame proximate to final fracture. This work should be helpful not only for providing good data to support fracture modelling by providing a good basis for developing regularization schemes, but also for materials selection purposes considering global and local formability.
2. Materials and Testing

Three 1000 MPa ultimate tensile strength (UTS) steel grades and two 1200 MPa UTS grades were used in this study. Both dual phase and multiphase grades with controlled additions of retained austenite in the microstructure were included in the study. Baseline material properties are presented in Table 1.

| Code   | Type       | Thickness (mm) | YS (MPa) | UTS (MPa) | TE (%) | UE (%) |
|--------|------------|----------------|----------|-----------|--------|--------|
| DP980  | Dual-Phase | 1.53           | 730      | 1047      | 14.8   | 8.7    |
| DP980T | Dual-Phase | 1.59           | 890      | 980       | 12.6   | 6.2    |
| DP1180 | Dual-Phase | 1.44           | 840      | 1227      | 14.0   | 6.8    |
| RA1000 | Multi-Phase| 1.56           | 630      | 1020      | 21.5   | 13.1   |
| RA1200 | Multi-Phase| 1.55           | 1090     | 1240      | 15.0   | 6.6    |

Uniaxial tensile testing was conducted on a 100 kN electro-mechanical test frame using standard full size ASTM E8 sheet specimens. Specimens were tested in longitudinal, transverse and diagonal orientations relative to the sheet rolling direction. Nominal strain rates of $10^{-3}$/s, $10^{-2}$/s and $10^{-1}$/s were used in this study.

3. Fracture Strain Measurement

3.1. Physical fracture strain measurement

To determine the true thickness strain on the fracture surface, a laser confocal microscope (Keyence model VK-X105) was used. In laser confocal optics, a pinhole in front of a photoreceptor ensures that no light other than that which passes through the focal point of the objective lens reaches the photoreceptor. Light from the laser source is focused on the sample via X-Y scan optics and the objective lens. The field of view is divided into 1024×768 pixels and reflected light from each pixel is detected by the photoreceptor to form the image. Figure 1 shows a typical sample with the fracture plane oriented normal to the microscope lens.

![Laser confocal microscope](image)

Figure 1. Laser confocal microscope used for thickness strain measurement.

Fracture morphology was observed to vary substantially even within one test specimen going from the left edge to right edge of the fracture surface. Variation observed for an RA1200 longitudinal...
sample tested at $10^{-3}$/s is presented in Figure 2 going from left edge to the center of the fracture surface.

![Left Edge](image1.png) ![Right Edge](image2.png)

**Figure 2.** Variation in fracture morphology in RA1200 longitudinal specimen tested at $10^{-3}$/s going from left edge to right edge of fracture surface.

True thickness fracture strain was measured at the left edge, center, and right edge locations, based on averaging the section profile over 50 sections and measuring the thickness associated with the top of the fracture surface (Figure 2). The effective thickness at fracture was determined as the weighted average thickness using weights of 1, 4, and 1 for the left edge, middle and right edge locations, respectively. The repeatability of the thickness measurement in one section (average of 50 sections) was within 0.010 mm; in terms of true thickness strain, error was estimated to be 1% strain. Width strain measurements were made using a traveling microscope with resolution to 5 decimal places. Measurements were made across the width section and also along the fracture plane. For a given specimen, the measurement repeatability in the width was within 0.10 mm. In terms of true width stain, the estimated error is less than 1% strain. Since the fracture event is statistical, in some conditions triplicate samples were tested. The maximum difference in measured true fracture strains was 6.5%.

3.2. **DIC fracture strain measurement**

All tensile tests were conducted using a 3D digital image correlation (DIC) system (GOM-Aramis-4M) for local displacement and strain measurement. The camera capture frame rate (10, 50, 250/s corresponding to $10^{-3}$/s, $10^{-2}$/s, and $10^{-1}$/s nominal strain rates respectively) was sufficient to allow good resolution of strain states close to fracture. Pixel resolution used was 0.052 mm/pixel and typical facet size selected was 14 pixels resulting in an effective gage length of 0.728 mm based on the default bilinear sub-pixel interpolation algorithm for the DIC measurement. Since the use of 3D DIC based strain measurement is becoming increasingly common including for capturing fracture strains, this work afforded the opportunity of comparing physical fracture strain measurement with a DIC approach. Two distinct fracture modes were identified with respect to the orientation of fracture in the specimens tested as shown in Figure 3 that necessitated slightly different approaches to identify the crack plane. In every case, paint stayed adherent to the specimen allowing correlation and strain measurement at the last frame before fracture.
Figure 3. Two distinct fracture modes observed in the tested specimens. Top image shows shear failure mode and bottom image shows transverse mode of failure.

Crack plane identification approach in the case of transverse fracture (bottom image in Figure 3) was to identify maximum and minimum displacement along the direction (X-axis) transverse to tensile axis (Y-axis) (Figure 4). A crack plane was drawn through two points (minimum and maximum transverse displacement) normal to the Z-axis. The average value of axial and thickness strain (computed from two in-plane principal strains based on volume constancy assumption) was determined from the crack section which is intersection of the crack plane with the sample X-Y. In the case of shear type fracture (top image in Figure 3), the average thickness strain points on both halves of the specimen was first identified (Figure 5). As before, a crack plane was drawn with these two points and normal to Z-plane. The average value of the axial and thickness strains were determined from the crack section which is intersection of the crack plane with the sample X-Y. Both approaches were processed on the last captured frame before fracture.

Figure 4. DIC method to determine true thickness and width strain for transverse type fracture.
4. Results and Discussion

True fracture strain data based on physical measurements of true thickness and width strains on the fracture surface are provided in Figure 6 for the three dual phase steels (DP980, DP980-TMP, DP1180) and two multi-phase grades (RA1000, RA1200) at the lowest strain rate of $10^{-3}$/s. The transverse true fracture strains were observed to be lower compared to longitudinal and diagonal directions for the majority of the steel grades in this study.

DIC based true fracture strain measurement data are provided in Figure 7 for comparison for tests conducted at a nominal rate of $10^{-3}$/s. Similar trends are observed in the DIC results in terms of orientation dependence although the true fracture strain values are somewhat lower. There are potentially several possible reasons for the observed differences between the physically measured strains and the DIC measured fracture strains: 1) The physical strains are measured directly on the fracture surface through the thickness whereas the DIC measurement is based on surface strain measurements close to but not at fracture; 2) Facet size used for DIC measurement was 14 pixels resulting in an effective gage length of 0.728 mm. Decreasing facet size to ~ 5 pixels has been advocated in reference [11] as a means to reduce gage length for DIC measurement to increase the measured fracture strains, but this approach of decreasing facet size was not feasible given the specimen volume of interest in the ASTM E8 full size tensile specimen.

Figure 5. DIC method to determine true thickness and width strain for shear type fracture.

Figure 6. True fracture strain based on physical measurement as a function of orientation at a nominal strain rate of $10^{-3}$/s.
Figure 7. DIC based measurement of true fracture strain at frame just before fracture.

Strain rate effect on the true fracture strain is presented for the transverse orientation in Figure 8, based on physical measurement of the fracture surface. The data appears to suggest an initial increase in true fracture strain with rate in DP980, DP1180 and RA1200 going from $10^{-3}$/s to $10^{-2}$/s but saturates thereafter.

Figure 8. True fracture strain variation with nominal strain rate based on physical fracture strain measurement.

A final observation noted in this study was that fracture modes appear to be sensitive to the sample orientation and strain rate. In DP980 and RA1200 samples, the longitudinal and the diagonal specimens failed in shear type failure mode independent of strain rate while the transverse specimens fractured normal to the tensile axis at $10^{-3}$/s and $10^{-2}$/s, but exhibited the shear-type fracture at $10^{-1}$/s. In the case of tempered DP980, in all cases a shear type of failure mode was noted independent of both orientation and strain rate. In the case of RA1000, transverse failure mode was observed in most test conditions. Selected replicate testing for RA1200 and DP980 in the transverse orientation generally confirmed the trends presented in Figure 9.
5. Global versus Local Formability

There is current interest in looking at measures of local formability (true fracture strain) along with measures of global formability (true uniform strain). Hance [10] has suggested two derived measures as well as a classification scheme that could be helpful in materials selection issues. The formability index is defined as the square root of the multiple between the true fracture strain and the true uniform strain and the local-global formability parameter is defined as the ratio between the true fracture strain and the true uniform strain [10].

![Figure 9](image1.png)

**Figure 9.** Fracture modes in DP980, RA1200 appear to be sensitive to orientation and strain rate.

![Figure 10](image2.png)

**Figure 10.** Plot of true fracture strain vs. true uniform strain at a nominal strain rate of $10^{-3}$/s.

In the original work [10], the data is presented only for transverse sheet orientation for different steel grades. However, this work shows (Figure 10) that it is important to consider the orientation...
effects carefully to avoid unintended consequences in material selection. Work is ongoing to establish the relationship between fracture strain and true uniform strain as a function of strain rate.

6. Conclusions

The effect of sample orientation and strain rate on uniaxial fracture strain has been studied in several dual phase and multiphase steels of interest in automotive structural applications. The following conclusions can be drawn from this study.

1. True fracture strain measurements on fractured specimens using confocal/optical microscopy tend to be substantially (20-30%) higher compared to DIC based measurement on frames close to eventual fracture. Trends in the data are however, quite similar.
2. In most of the steels investigated in this study, the transverse true fracture strain is substantially lower than longitudinal and diagonal directions (in some instances up to 40%).
3. The larger measured anisotropy in true fracture strains may have substantial implications in material selection considerations based on looking at global versus local formability.
4. Fracture modes were found to be sensitive to sample orientation and strain rate, particularly in DP980 and RA1200 grades.

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