Formability of Advanced High Strength Steels

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ABSTRACT: Novel draw-bend tests of 3 dual-phase (DP) steels utilizing velocity control of both actuators revealed three patterns of failure depending on draw speed, draw speed ratio, and R/t ratio. Shear failure occurs preferentially for smaller R/t and higher deformation rates. During draw bend tests, the temperature rises are significant, up 100 °C before necking, with consequent loss of strength in affected regions. A novel 1-D constitutive equation relating flow stress to strain, strain rate, and temperature was developed based on tensile tests. FE simulations using the measured constitutive response predicted the types of failures accurately, without introducing damage mechanics. The deformation-induced heating is a critical part of the failure process.

KEYWORDS: Advanced high strength steel, Shear failure, Thermally-assisted strain localization, Thermo-mechanical finite element model

1   INTRODUCTION

DP steels are a class of advanced high strength steel (AHSS) in wide and increasing use in the automotive industry. Depending on the application and the grade, failures in AHSS are not always able to be predicted by the usual forming simulation and application of forming limit diagrams (FLD). Such diagrams represent the forming limit based on localized deformation, or necking, which has proven successful in predicting failures for conventional sheet steels. The new type of failure, so-called "shear fracture", was observed at sharp radii where bending and unbending under tension during forming occurred [1].

The draw bend test mimics the mechanics of deformation of sheet metal as it is drawn, stretched, bent and straightened over a die radius entering a typical die cavity, Fig. 1 [2]. The test can produce both normal plastic localization/necking and shear fracture. For AHSS, the flow stress is affected significantly by deformation induced heating at even modest strain rates, so the constitutive equation must take into account these effects [3]. Deformation induced heating is usually expected to have a detrimental effect on ductility [4].

The objective of this research is to construct maps of failure type and normalized maximum sheet tensions as functions of R/t and strain rate for 3 DP steels from draw bend tests and to improve FEM predictability by taking into account thermal effect with a new 1D constitutive equation relating flow stress to strain, strain rate, and temperature.
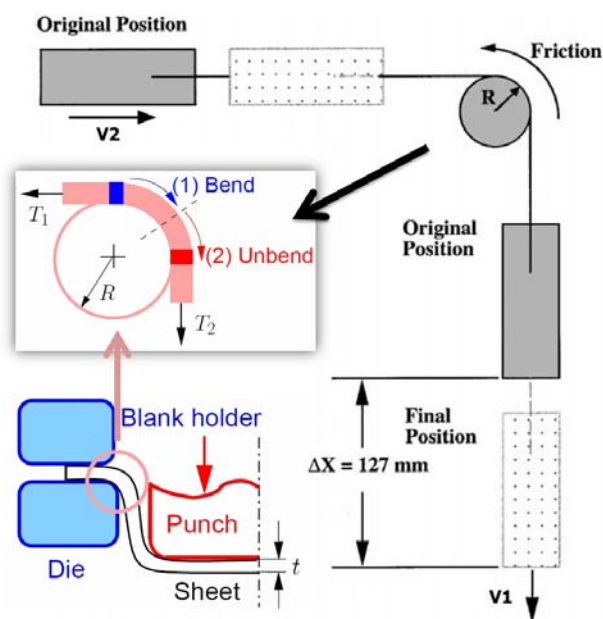

Figure 1: Schematic of draw-bend test

2   DRAW-BEND FRACTURE TEST

Novel draw-bend fracture (DBF) testing is based on a modification of draw-bend tests that have been used for friction and springback testing, as shown in Fig. 1. For typical springback or friction applications, a strip of sheet metal is constrained and bent 90 degree around a roller by two grips. While one (back) grip applies constant back force to the sample, the other (front) grip pulls the sample away from the roller at a constant

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speed, V_1, so that material moves over the roller under controlled conditions. In DBF test developed here, the speed of the back grip, V_2, is controlled instead of the force as shown in Fig. 1. This guarantees the forward movement of sample, thus fracture always occurs toward the front leg of the specimen (which is not guaranteed otherwise, leading to difficult-to-interpret results). Sheet samples having width of 25mm are used with fixed rollers and lubricants to mimic typical forming processes. The test proceeds until the sample fails, either by tensile plastic localization/necking or by shear failure, depending on the material properties and testing conditions (die radius, draw speeds, sheet thickness).

DBF tests of three DP steels: DP590, DP780 and DP980, revealed three patterns of failure based on process conditions: Type I is a standard tensile failure far removed from small radius bending regions. It occurs in material that has not been bent and unbent over the die radius. Type III is what is often called "shear failure" that occurs at the exit tangent point with little deformation in the width direction, in a direction perpendicular to the strip axis. Type II has a mixed appearance that appears to initiate like Type III but propagates at an angle in material that has been drawn over the tooling. Type II and Type III failures, here associated with what are typically called shear failures, occur preferentially for smaller R/t and higher deformation rates, Figs. 2 and 3. In order to understand the origin of the phenomena involved, temperatures were measured during draw bend deformation using thermocouples and an infrared camera. The temperature rises were significant, up 100 °C at locations near from the localization depending on failure type and forming rate. Therefore, thermo-mechanical analysis using temperature-sensitive constitutive relations is essential to understanding the behavior
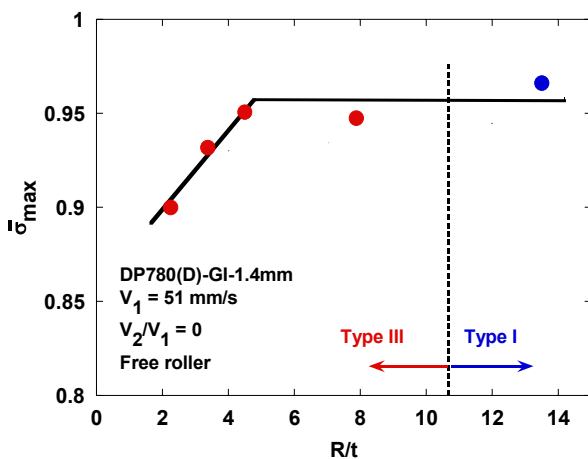

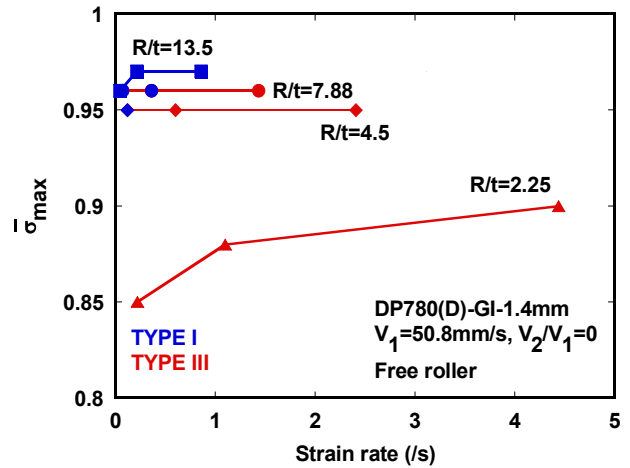**Figure 2:** Normalized maximum stress and failure types at various R/t

Figure 3: Normalized maximum stress and failure types at various strain rates

3 CONSTITUTIVE EQUATIONS

In order to capture the essential behavior, a novel constitutive equation ("H/V") relating flow stress to strain, strain rate, and temperature was developed as follows:

$$\sigma(\varepsilon,\dot{\varepsilon},T)=\left[\alpha(T)f_{Hollo}+(1-\alpha(T))\cdot f_{Voce}\right]\cdot\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^m\cdot\left[1-D(T-T_{RT})\right] \quad (1)$$

where $\alpha(T)=\alpha_1-\alpha_2(T-T_{RT})$, f_{Hollo} is Hollomon equation ($\sigma=K\varepsilon^n$), f_{Voce} is Voce equation ($\sigma=A(1-Be^{-Cn})$), T and T_{RT} are current and room temperature, respectively, m is a rate sensitivity parameter, and D, α_1, and α_2 are material constants. The constitutive equation was determined based on tensile tests at various test conditions, 3 temperatures and 4 strain rates. As can be seen from Fig. 4, three constitutive equations, H/V, Hollomon and Voce models, all showed good agreement with tensile test data in the region of strains attainable with a tension test, but clear differences are seen at higher strains. Balanced biaxial bulge test results at room temperature confirmed that the H/V model was in better agreement in the high strain region than either Hollomon or Voce equations, as shown in Fig. 4.
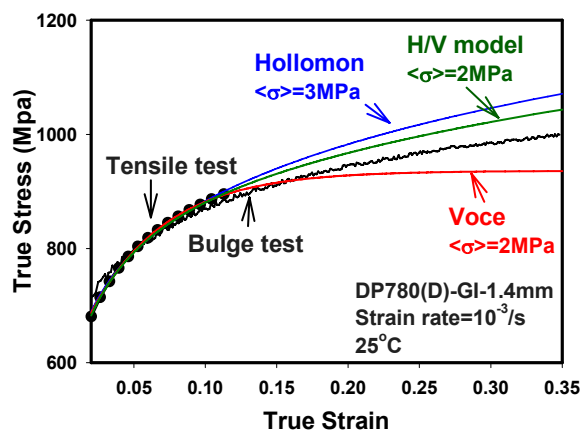
Figure 4: Comparison of 1D constitutive model with balanced biaxial bulge test

4 THERMO-MECHANICAL FINITE ELEMENT ANALYSIS

A thermo-mechanical finite element model of draw-bend tests was developed to investigate the failure mechanisms of AHSS deformation. The model accounts for deformation heating and heat transfer and is capable of representing softening and altered strain hardening of materials measured at elevated temperatures. Such capability was required because temperatures rise much beyond room temperature during draw-bend tests by deformation heating. A symmetric 3D solid model (C3D8RT) was used with 5 layers through thickness in Abaqus 6.7 Standard. Isotropic yield and isotropic hardening were assumed for simplicity. Thermal coefficients were measured from independent experiments or obtained from the literatures. The friction coefficient was based on a comparison of forces of front grip and back grip between FE simulation and DBF test using Coulomb friction law.

As can be seen from Figs. 5-7, all three types of failures were predicted accurately (Type I – tensile, Type II – mixed, Type III – shear) and the draw distances to failure were predicted within 5-20 percent of the measured ones. Isothermal simulations significantly over-predicted the draw distances to failure, by up to 100 percent (Fig. 7). (Note: the engineering draw stresses are normalized to the assumed ultimate tensile stress corresponding approximately to the maximum strain rates and room temperature, as follows: DP590 – 642 MPa, DP780 - 835 MPa, and DP980 – 1014 MPa.)
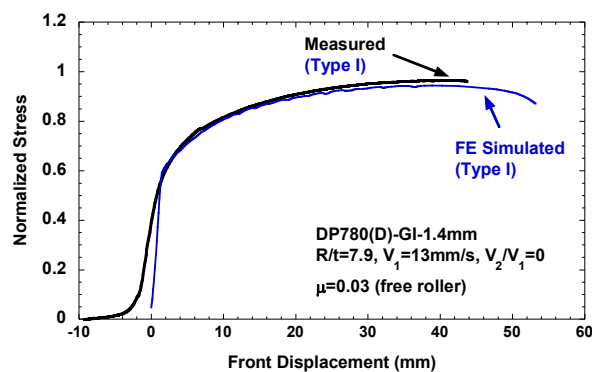

Figure 5: Thermo-mecahnically FE simulated and measured stress-displacement curves, Type I.
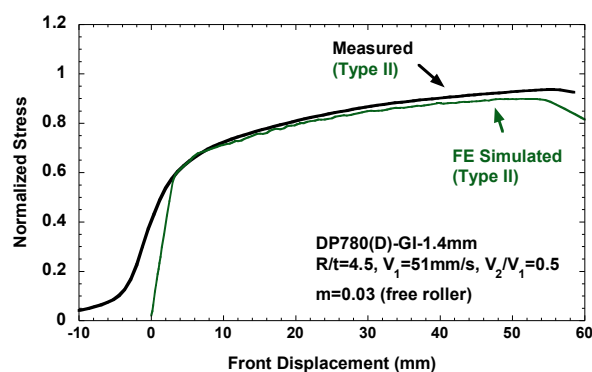

Figure 6: Thermo-mecahnically FE simulated and measured stress-displacement curves, Type II.
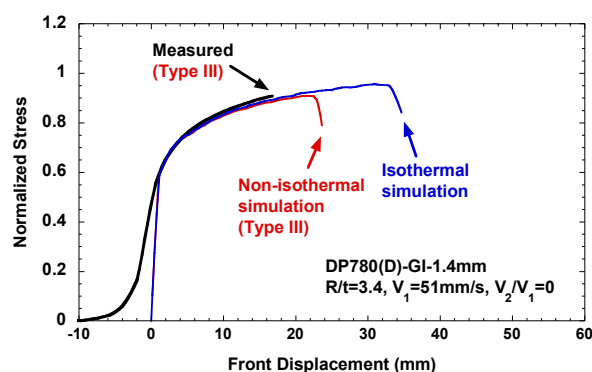

Figure 7: Thermo-mecahnically FE simulated and measured stress-displacement curves, Type III.

The normalized maximum stresses are compared as a function of strain rates in Fig. 8, along with colors corresponding to failure type. While the normalized stress to failure changes little, the failure type changes from Type I to Type III (tensile localization to shear failure) as the strain rate increases. This result suggests that shear failure is a consequence of thermally-assisted strain localization, in agreement with Fig. 7
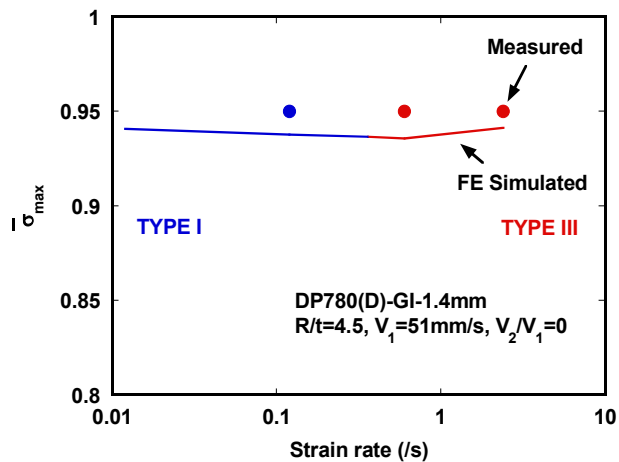
Figure 8: *Comparison of simulated and measured maximum stresses at various strain rates*

5   CONCLUSIONS

Maps of failure type and normalized maximum sheet tensions have been measured and simulated with good accuracy as functions of R/t and strain rate for DP steels. Deformation induced heating and consequent material softening is a critical part of the failure process at typical strain rates. The results suggest that damage is not an important component of "shear" failures observed, at least with these alloys under these conditions.

ACKNOWLEDGEMENT

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