Numerical Modeling of DP780 Tubular Hydroforming

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ABSTRACT: By substituting conventional steel with advanced high strength steels (AHSS) in the hydroforming process, vehicle weight reduction can be achieved. This work focuses on finite element modeling and analysis of straight and pre-bent hydroformed Dual Phase 780 steel tubes. The extended stress-based forming limit curve (XSFLC) failure criterion was used to predict failure (burst) in the straight tube hydroforming models. The Keeler-Brazier approximation and free-expansion burst tests were used to define the XSFLC. Two levels of boost were applied to the pre-bending models. Three levels of end-feed (EF) were used for the straight and pre-bent hydroforming simulations. Improved formability was shown for increased EF in the straight tube hydroforming models. Greater pre-bending boost resulted in tubes with a greater overall thickness around the circumference of the tube.

Key words: Hydroforming, Advanced High Strength Steel, Numerical Modeling, Failure Criterion

1 INTRODUCTION

The main advantage of replacing conventionally stamped and welded automobile structural components with hydroformed ones is weight reduction. By substituting conventional steel tubes (currently in use) with advanced high strength steel (AHSS) tubes, weight reduction can be further improved due to a reduction in part thickness.

Dual Phase (DP) steel is a subgroup of AHSS, which has a higher formability (due to its low yield strength to tensile strength ratio), more uniform elongation and higher work hardening rate than other AHSS [1]. Its improved formability over commercial high strength steels makes it a potential candidate for replacing the convention steel tubes used in current hydroforming automotive applications. For this reason, DP780 (which will be used for future experimental work) was selected for this study.

Pre-bending and hydroforming numerical models were created using the dynamic explicit code LS-DYNA. The extended stress-based forming limit curve (XSFLC) failure criterion [2] was used to predict failure (burst) pressure. The XSFLC method is based on the strain-based forming limit curve (εFLC) of the material in question; hence, an accurate εFLC of the DP780 material was required. Originally, the XSFLC criterion was developed using the Keeler-Brazier (KB) approximation to define the εFLC, but the experimental and numerical work of Bardelcik and Worswick [3] and Sorine *et al.* [4,5] showed that the KB method over predicted the failure pressure. In addition to using the KB method, the upper and lower bound (UB/LB) εFLC method as presented by Sorine *et al.* [4,5] was used to define the XSFLC failure criterion.

Previous numerical and experimental hydroforming work on pre-bent steel tubes showed that increased boost during pre-bending reduced thinning around the circumference of the bend which elevated the burst pressure and corner-fill expansion (CFE) in subsequent hydroforming operations [6]. Also, an increase in burst pressure and CFE was observed for hydroforming experiments where an axial end-feed (EF) load was applied during hydroforming for both straight and pre-bent tubes [3,5,6].

For this work, pre-bending models were created and boost levels of 100% and 105% were simulated. Subsequently, these models, along with straight tube models, were hydroformed with three levels of end-feed. Failure was predicted using the XSFLC failure criterion with the KB and UB/LB methods of defining the εFLC as discussed previously.

1.1 Tensile Testing and Friction Characterization

The tube blanks used in the numerical models are based on Dofasco DP780 tubes that have an OD of 76.2 mm (3”) and a nominal thickness of 1.54 mm. Uniaxial tension tests of DP780 tubular specimens were conducted at various orientations around the circumference of the tube (weld seam was neglected). Figure 1 shows the average true stress *vs.* strain curve that was fit with the power law function to obtain a strain hardening exponent (n) of 0.130 and strength coefficient (K) of 1168 MPa. The coefficient of friction used for the pre-bending and hydroforming models are the same as those measured by the twist compression test for DP600 tubes in [7].

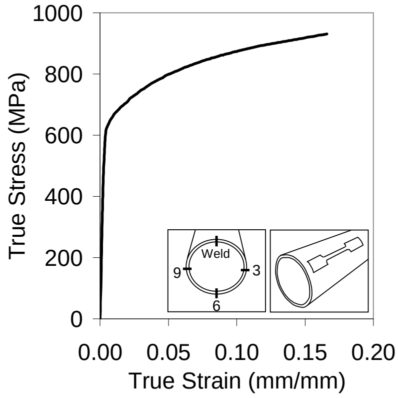

Figure 1: DP780 stress *vs.* strain (true) curve.

1.2 Tube Bending Models

The tube bending models are based on the fully instrumented Eagle Technologies mandrel rotary-draw tube bender at University of Waterloo [6, 8]. The centreline radius to tube diameter ratio (R/D) used for this work was 2.0. In addition to the nominal 100% boost bend, a 105% boost case was modelled as well. Bending boost is defined as the ratio of pressure die displacement to the arc length swept by rotary die [6, 8].

The tube bender tools were modelled with a rigid material model and meshed with four noded quadrilateral shell elements. The tube was meshed with five through thickness, eight node constant stress brick elements which obeyed the Von Mises yield criterion. The constitutive model of the tube follows the average true stress *vs.* strain curve in figure 1. The coefficient of friction (COF) between the tube and the bender tools was set to the measured COF values from [7]. Half symmetry was used to reduce computational time. LS-DYNA was used to solve the following pre-bent models; pre-bending (explicit), springback (implicit), die close/EF ram insertion (implicit) and hydroforming (implicit). The implicit code was used to solve the straight tube hydroforming models as well.

1.3 Hydroforming Models

The straight and pre-bent hydroforming models are based on the experimental facilities at the University of Waterloo [6, 8]. During hydroforming, the EF rams applied EF loads of zero, 67 kN and 133 kN as described in [3, 6]. Formability was quantified by measuring the corner-fill expansion (CFE) at the predicted failure pressure [6]. The pre-bending tube boundary conditions were applied to the pre-bent hydroforming models, while the straight tube was modeled with 1/16th symmetry and the appropriate boundary conditions.

2 FAILURE CRITERIA

The extended stress-based forming limit curve (XSFLC) failure criteria was used to predict failure in the straight tube hydroforming models. Two different methods were utilized to create the strain-based forming limit curves (εFLC) which define the XSFLC. These two methods were the Keeler-Brazier approximation [9] and free-expansion burst tests to define and upper and lower bound εFLC as shown by Sorine *et al.* [4].

2.1 Keeler-Brazier Approximation

Based on the strain hardening exponent (n) of 0.130 and thickness (t) of 1.54mm, the plane strain intercept (FLC_o) for the DP780 is 0.279, according to Keeler and Brazier. The shape of the εFLC was digitized from [9] and is shown in figure 5a. Using the method of Simha *et al.* [2], the εFLC was converted into XSFLC stress space (figure 5b).

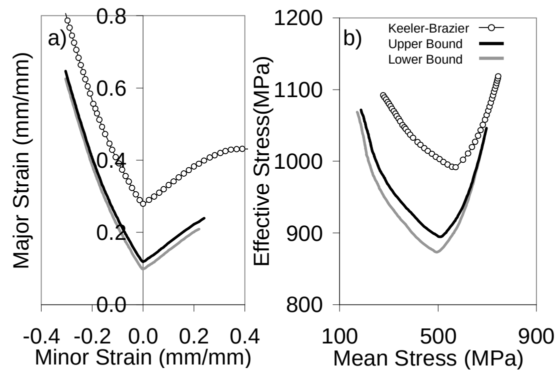

Figure 5: DP780 a) Strain based (eng) FLC's and b) XSFLC's.

2.2 Free Expansion Burst Test Method

Free expansion burst tests were performed with the DP780 tube at Dofasco R&D. Information about the test apparatus can be found in [10]. During the test, the centre of the bulging tube follows a plane-strain path. The radial expansion *vs.* internal pressure of multiple burst tests are shown in figure 6.

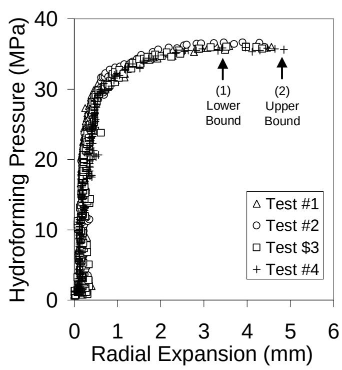

Figure 6: DP780 free-expansion burst test results.

Necking is said to occur between the maximum pressure (1) and the expansion at burst (2). Using the radial expansion at these two points, a lower bound

(LB) and upper bound (UB) plane-strain intercepts were calculated. The shape of the εFLC was digitized from [9] and shifted accordingly (figure 5).

3 BENDING RESULTS

Thickness measurements were taken at the inside of the bend, outside of bend and 360º around the circumference as shown in the figure 7 insets.

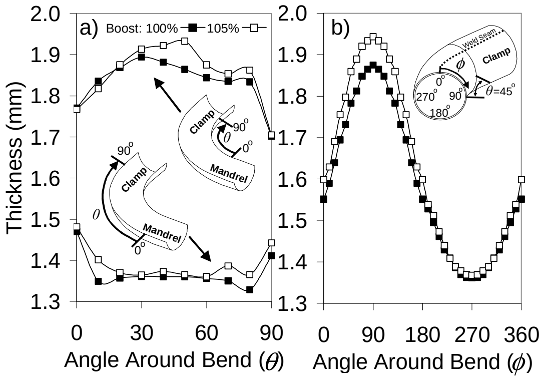

Figure 7: Thickness distribution around a) inside and outside of the bend b) 360º around the circumference of the bend.

Thickening occurred at the inside of the bend due to the sum of the compressive bending and membrane stress while thinning occurred at the outside of the bend due to the tensile bending and membrane stress (figure 7a). The thickness distribution around the circumference of the bend follows a sinusoidal distribution with maximum thickening at the inside of the bend (ϕ=90º) and maximum thinning occurring at the outside of the bend (ϕ=270º).

The 105% bending boost case shows increased thickening across the entire circumference of the bend due to the additional axial compressive stress that is imposed on the tube during pre-bending [6].

4 HYDROFORMING RESULTS

4.1 *Straight Tube Hydroforming*

Figure 8a plots the predicted failure pressure and corner-fill expansion (CFE) *vs.* end-feed (EF) load for the straight tube hydroforming models.

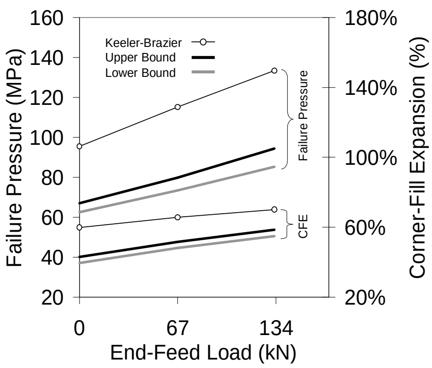

Figure 8: Predicted failure pressure and CFE *vs.* EF load straight tube hydroforming.

Both the Keeler-Brazier (KB) and the free-expansion burst test (UB/LB) methods of defining the strain-based FLC (εFLC) show an increase in predicted failure pressure for increased EF load. The KB method predicts an approximately 40% greater failure pressure across the entire range of EF loads. Consequently, the predicted corner-fill expansion (CFE) is greater for the KB method as well. Using the UB results, an increase in EF load from zero to 133kN increased the failure pressure from 67MPa (43% CFE) to 94MPa (59% CFE). Figure 9a illustrates the effect of EF on the thickness distribution around the circumference of the straight tubes. The KB and UB/LB methods show thinning at the tube/free expansion die contact region as shown in [3, 6]. The KB method predicts a large thickness reduction, which is unrealistic for such a high strength/low formability material, showing that the KB method over predicts failure pressure.

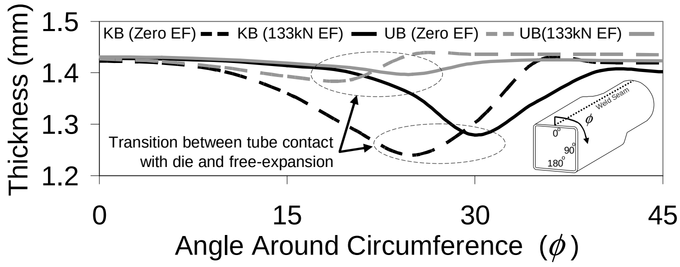

Figure 9: Straight tube thickness around circumference.

4.2 *Pre-Bent Tube Hydroforming*

For the pre-bent hydroforming models, the XSFLC method consistently predicted failure at the outside of the bend first (lowest pressure), then the inside of the bend and finally at the neutral axis of the bend (highest pressure). The prediction of the multiple failure sites are an artefact of the XSFLC assumptions that take into account the pre-strain from pre-bending [2]. For the purpose of this work, the thickness distribution of the models at two different hydroforming pressures were evaluated. Figure 10 shows the circumferential thickness distribution for pre-bent tubes (100% boost) that were hydroformed with zero and 133kN of end-feed (EF). The two interrupted pressures that were selected for the analysis were 44MPa and 71MPa.

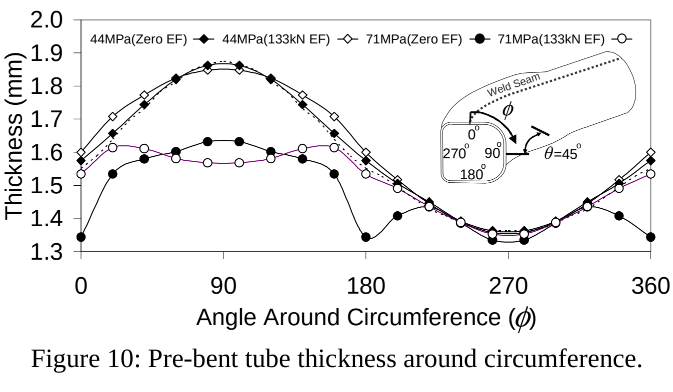

Figure 10: Pre-bent tube thickness around circumference.

For the 44MPa distributions, it is obvious that little deformation has occurred because the thickness distribution changes little compared to the pre-bent tube which is shown with the dashed line.

For the 71MPa models, a big thickness reduction was observed at the inside of the bend (ϕ=90º) for both EF cases. Although the thickness reduction is large, the initial thickness of the tube at ϕ=90º is also large due to thickening during pre-bending. Failure is not likely to occur here. The more significant thickness reduction occurs at the neutral axis of the tube (ϕ=0º/360º and ϕ=180º) for the zero EF case. Here, the zero EF tube experiences a big thickness reduction which is synonymous to a neck. This local neck has been observed for interrupted pre-bent DP600 hydroforming experiments [5,6]. It is the compressive stress provided by the EF rams that allows more material to flow into the die cavity and allow the tube to suppress necking.

Because the 105% boost pre-bent tube (figure 7) had a greater overall thickness than the 100% boost case, one can assume that a higher internal pressure can be supported, which would consequently allow the tube to expand to a greater corner-fill expansion.

5 CONCLUSIONS

As a result of the numerical study, the following conclusions can be made:

- Increasing bending boost from 100% to 105% resulted in a greater overall thickness around the circumference of the tube because of the additional axial compressive stress. If subsequently hydroformed, it is expected that the 105% boost tube would be able to withstand a greater hydroforming pressure, resulting in greater corner-fill expansion. Experimental validation is required.
- The Keeler-Brazier method of defining the εFLC for the XSFLC failure criterion resulted in predicted failure pressures that showed local areas of severe thinning for the straight tube hydroforming models. This is unrealistic for a high strength/low formability steel such as DP780.
- The UB/LB method was also used to define the εFLC for the XSFLC. The εFLC was considerably lower than the εFLC predicted by the KB approximation. In straight tube hydroforming, the UB/LB method predicted failure pressures at which the thickness distributions showed more realistic levels of thinning, as observed in previous work on DP600 tubes [3, 6]. A 27% increase in corner-fill expansion was observed when the end-feed load during hydroforming was increased from zero to 133kN.
- Pre-bent tube hydroforming models showed that considerable thinning occurred at the neutral axis of the tube when no EF was used. The thinning was suppressed when 133kN of EF was applied to the tube because the additional material was being fed into the die cavity be the EF rams.

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