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Introduction of a 1000 MPa crush tip within a Usibor® 1500-AS axial crush rail using in-die heated hot stamping

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Abstract. Axial crush is an important mechanism used in automotive front end structures to absorb impact energy. In this work, numerical simulation is used to investigate the crush response of a Usibor® 1500-AS axial crush rail with tailored properties achieved using in-die heated (IDH) hot stamping. In this case, the targeted properties in the softened zone correspond to a tensile strength of 1000 MPa. A finite element model is utilized to predict the crash performance of the tailored in-die heated 1000 MPa crush tip within a Usibor® 1500-AS rail. A numerical parametric study is presented, comparing the crush response based on fracture *loci* determined using two different plane-strain strain experiments, one the plane-strain Nakazima dome test and the other the VDA-238 V-bending test. In addition a number of different mesh regularization treatments are considered. The predictions exhibit a strong dependency of the onset of fracture upon the plane strain fracture strain level and degree of mesh regularization.

1. Introduction

Government regulations to reduce automotive fuel consumption have automotive manufacturers expending considerable effort on decreasing the weight of structures within their vehicles. One lightweight solution, originally employed on vehicles in 1984 by Saab Automobile AB [1], is to use hot formed ultra-high strength steel (UHSS) in locations where occupant intrusion resistance is paramount due to its high strength (but low ductility). However, automotive manufacturers have been reluctant to adopt UHSS in frontal crash structures due to its susceptibility to fracture at low strains relative to advanced high-strength steel (AHSS).

The introduction of tailored in-die heated hot stamping makes UHSS a viable material option in frontal crash structures, thus presenting an opportunity for vehicle weight reduction. Tailored IDH hot stamping with Usibor® 1500-AS has been demonstrated by George [2] in a B-pillar and Omer [3] in an axial crush member to increase both crash energy absorption and fracture resistance. The benefit in the tailored IDH process stems from multi-functionality in a single part, with the rapidly quenched (cooling rate greater than 30°C/s [4]) high strength martensitic zones inhibiting collapse to provide protection against intrusion into the passenger compartment and the slowly cooled (cooling rate less than 30°C/s [4]) more ductile bainitic/ferritic zones providing crash energy absorption.

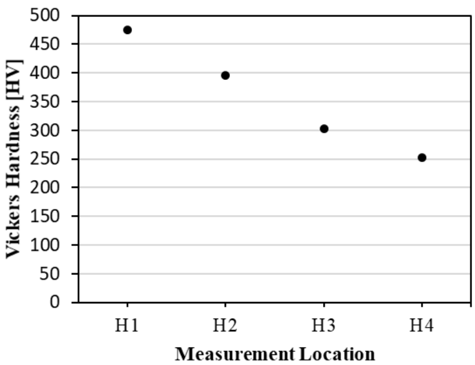
This work represents a preliminary numerical investigation of the suitability of IDH tailored hot stamping of Usibor® 1500-AS to create a 1000 MPa UTS crush tip within an axial crush rail. Prior to forming actual parts, numerical simulations are used to investigate the structural response, in particular examining the likelihood of fracture during progressive folding. A numerical parametric study comparing the crush response of an axial crush rail using equivalent fracture strains generated with either the plane-strain Nakazima dome test [5] or the VDA-238 V-bending test [6] is considered. Both plane strain failure limits were considered in the failure strain *versus* triaxiality *locus* adopted within the Generalized Incremental Stress-Strain Model (GISSMO) [7]. It is hypothesized that in the plane-strain region of the fracture *locus*, the plane-strain Nakazima dome test provides far more conservative equivalent fracture strains than the VDA-238 V-bending test. The effect of mesh regularization on the fracture predictions is also considered.

2. Material

The material studied is 1.2 mm thickness Usibor® 1500-AS, a hot stamping boron steel that reaches ultra-high strength through die quenching. According to ten Kortenaar [8], the ultimate tensile strength of fully quenched Usibor® 1500-AS is 1571 MPa, which is within the typical range of 1300 to 1600 MPa.

Experiments conducted by Bardelcik *et al.* [9] on miniature dog-bone specimens at quasi-static strain rate, have shown that a 1041 MPa UTS corresponds to a Vickers hardness of 339 HV. Thus, the target hardness to produce 1000 MPa UTS tailored Usibor® 1500-AS should be slightly below 339 HV.

George [2] has examined the relationship between die temperature and resulting hardness during die quenching of an IDH tailored lab scale B-pillar, illustrated in Figure 1. Locations H1 and H2 correspond to the fully quenched "hard" zone, while locations H3 and H4 correspond to a tailored "soft" zone achieved using a 300°C die temperature. Location H3 exhibits a hardness of 300 HV, while a somewhat lower hardness is achieved at location H4 which is a sidewall region that experiences higher strain. Thus, a die temperature slightly lower than 300°C is expected to produce a 1000 MPa UTS tailored Usibor® 1500-AS formed part.



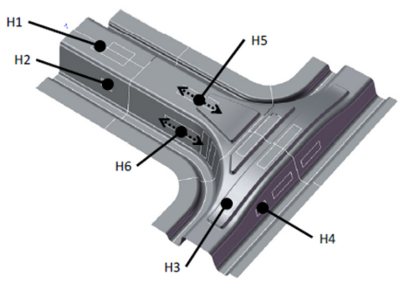


Figure 1. Vickers hardness measurements for the 300°C die quench condition (George [2]), showing that a 300 HV hardness is produced at location H3.

3. Numerical model setup

The numerical modelling in this work was performed using the commercial finite element (FE) software LS-DYNA R9.01. Meshing and model setup were performed in HyperMesh 2017.2. The subsequent sections will describe the constitutive model development (Section 3.1), the adopted fracture loci (Section 3.2) and the axial crush rail crash model (Section 3.3).

3.1. Constitutive model development

The purpose of the constitutive model development section is to ascertain the Vickers hardness that will produce a 1000 MPa UTS tailored Usibor® 1500-AS formed part and then to assign the relevant material properties (work hardening response) to the numerical model. The constitutive response can be determined as a function of as-quenched Vickers hardness using the model developed by Bardelcik *et al.* [9] and further developed by Omer *et al.* [10]. In the current study, six different Vickers hardness levels were considered 400, 380, 360, 340, 320 and 300 HV, as observed in Figure 2(a). To extract the UTS from the true stress *versus* effective plastic strain curves they first had to be converted into engineering stress and plastic strain values. Using volume conservation, the instantaneous cross-sectional area of the JIS tensile specimen is calculated from the effective plastic strain. Finally, the engineering stress is calculated based on the true stress and change in cross-sectional area and the elastic strain is then added to the converted engineering plastic strain to obtain total engineering strain (Figure 2(b)). Note that such a conversion neglects damage and fracture processes, but was judged adequate for the current numerical study.

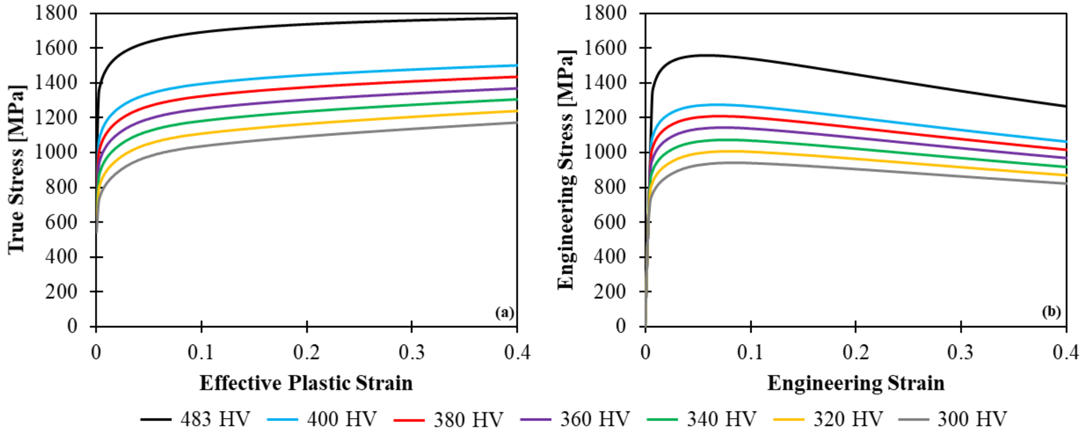


Figure 2. True stress *versus* effective plastic strain (a) from Bardelcik *et al.* [9] converted into engineering stress *versus* engineering strain (b) to identify the UTS at each hardness level.

The UTS *versus* Vickers hardness predicted for each case is shown in Figure 3. For validation purposes, measured UTS *versus* hardness data from ten Kortenaar [8] (fully quenched condition) and Bardelcik *et al.* [9] (tailored condition) are also plotted (symbols) and agree reasonably well with the predictions. A linear trend in Vickers hardness *versus* UTS is observed in Figure 3 for the constitutive model prediction. The linear trend is attributed to the fact that the flow stress curves for each specified hardness level are linear interpolations between experimentally quantified flow stress curves produced by Bardelcik *et al.* [9]. Interpolation of the linear portion of this curve indicates that the Vickers hardness corresponding to a 1000 MPa tensile strength tailored Usibor® 1500-AS is 317 HV. This prediction is a reasonable because it is slightly lower than the 339 HV measured by Bardelick *et al.* [9] to produce a 1041 MPa UTS.

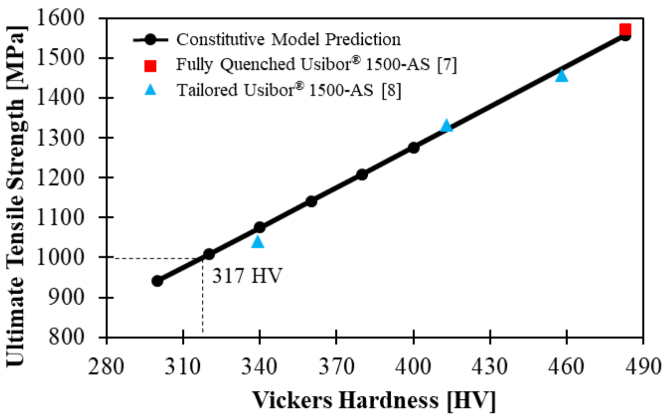


Figure 3. Constitutive model predicted UTS based on Vickers hardness and measured UTS based on hardness from ten Kortenaar [8] (fully quenched) and Bardelcik *et al.* [9] (tailored).

The work hardening curves using the model of Bardelcik *et al.* [9] for the hard (483 HV) and soft (317 HV) as-quenched conditions are plotted in Figure 4, which shows the stress-strain curves at various strain rates (0.001, 0.01, 0.1, 1, 10, 100 and 1000 s^{-1}).

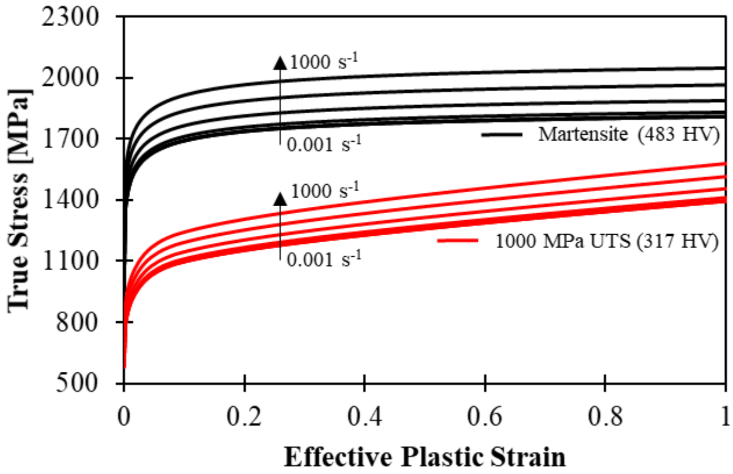


Figure 4. Flow stress curves of IDH tailored Usibor® 1500-AS for martensite (Omer *et al*. [10]) and 1000 MPa UTS condition (HV = 317) using the ETCM model due to Bardelcik *et al.* [9].

3.2. Fracture loci
Fracture *loci* were developed for the two material conditions that also considered the effect of the adopted plane-strain limit strain used to fit the fracture *locus* within the GISSMO failure model [7]. Plane strain equivalent fracture strain values from two different experiments are considered, one generated from the plane-strain Nakazima dome test and the other from the VDA-238 V-bending test. Figure 5 compares failure *loci* for two material conditions (the fully quenched martensitic condition and the 400°C die quench condition) fit using the two different plane strain experiments. Currently, failure *loci* for a 1000 MPa strength condition is not available, so the *loci* from the two available material conditions (martensite and 400°C die quenched) were linearly interpolated using the material hardness values.

To account for various element sizes a regularization factor was applied to the curve based on the element size used in the hat channel rail mesh. The regularization parameter was varied within the numerical parametric study. A lower mesh regularization parameter has the effect of scaling down (reducing) the fracture strain, thus increasing the likelihood that fracture will be predicted. The trial parameters and corresponding trial number used in the parametric study are displayed in Table 1. Note that the regularization parameter value of 0.63 was that used by Omer *et al.* [10] in conjunction with the plane-strain Nakazima dome failure *loci*. The value of 0.55 corresponds to a regularization based on a biaxial dome model, while the value of unity corresponds to a case without regularization which would represent an upper bound on the failure strain in the simulation. For brevity, the trial numbers in Table 1 are used in the following text describing the model predictions.

Table 1. Breakdown of parameters used in each trial number.

	Trial 1	Trial 2	Trial 3	Trial 4
Plane-Strain Eq. Fracture Strain Data Source	PS Dome	V-Bending	V-Bending	V-Bending
Regularization Parameter at 2.5 mm Element Size	0.63	0.55	0.63	1.00

It is apparent from Figure 5 that the equivalent fracture strain in the plane-strain region is higher for each material condition in the V-bending test than it is for the plane-strain Nakazima dome test. The higher fracture strain measure from the V-bend experiment is attributed to the bending stress state which tends to suppress localization (necking). In contrast, the plane-strain Nakazima dome experiment experiences necking prior to fracture making it difficult for the Digital Image Correlation (DIC) measurements to capture the final fracture strain. High strain gradients in the neck region result in averaging of the local fracture strain due to inherent DIC gauge length, which leads to the underestimation of fracture strain in the plane-strain Nakazima dome test.

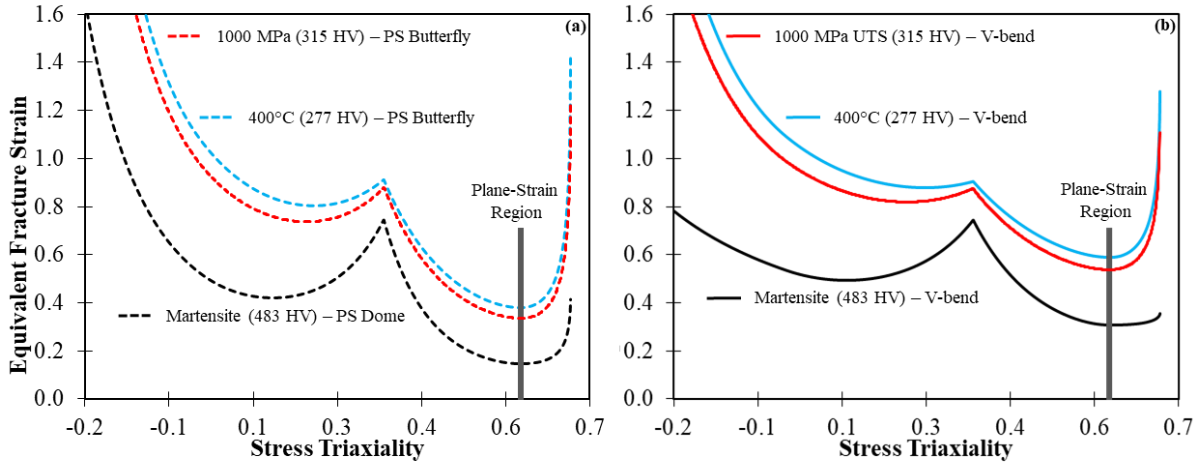


Figure 5. Fracture loci of IDH tailored Usibor® 1500-AS for the martensite and 400°C die quench conditions (Omer et al. [10]), as well the interpolated 1000 MPa UTS condition using Nakazima dome (a) and V-bending (b) data.

3.3. Axial crush rail crash model

The purpose of the axial crush model is to predict whether an as-quenched material condition corresponding to a strength of 1000 MPa will possess the ability to crush in a ductile fashion without fracture. Such performance is important in assessing whether this material condition will be suitable for crash energy absorption.

An explicit dynamic mechanical solver is utilized in the axial crush model. All of the elements are 2.5 mm Belytschko-Tsay shells with 7 through-thickness integration points. The material properties were assigned to the axial crush rail in two zones; a soft zone and a hard zone. The soft zone in this study is the 1000 MPa strength condition found from the constitutive model predictions to occur at 317 HV. The hard zone refers to the fully martensitic condition with a hardness of 483 HV. The assignment of these material properties can be observed in Figure 6, which illustrates the hard zone in red and soft zone in blue.

A fold initiator is introduced 70 mm from the 1000 MPa strength end by displacing two rows of thirteen nodes (a total of twenty six) 4 mm inwards along the y-direction. In addition, spot welds were modelled every 25 mm along the length of the axial rail assembly flanges to connect the two halves. The spot welds are modelled as linear elastic steel beams. Note that failure of the spot welds was not considered in the current work, but will be added in future work as failure characterization results become available.

The length of the soft zone is 300 mm while the length of the hard zone is 200 mm, for a total rail length of 500 mm. The fixed end is modelled by constraining 50 mm of nodes in all six degrees of freedom. A boss, outer clamps and mounting plate, modelled as rigid, are tied to the free end of the crash specimen. The 855 kg crash sled is modelled as a rigid plate of shell elements and given an initial velocity of 10.6 m/s. These boundary conditions are illustrated in Figure 6.

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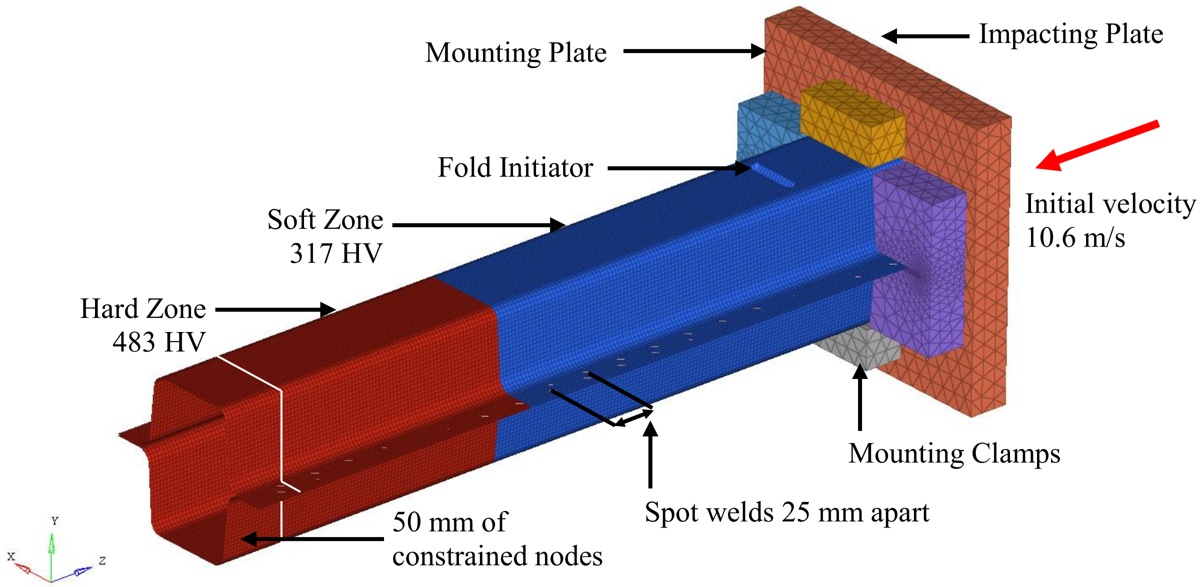

Figure 6. Setup of the axial crush model showing the fully martensitic hard zone (red) and the intermediate 1000 MPa strength soft zone (blue).

4. Axial crush rail predictions

In this numerical parametric study, the plane-strain region of the fracture *loci* have either been generated from the plane-strain Nakazima dome test or the VDA-238 V-bending test. In addition, the regularization parameter used for the 2.5 mm element size is varied for the V-bending fracture *loci*.

In the first 6.5 ms of the crash simulation, folding of the sidewall, flange and top of rail is initiated for all trials, as illustrated in Figure 7. The elemental integration point average damage value contour, plotted in Figure 7, illustrates that more damage is predicted when the plane-strain region fracture strain comes from the plane-strain Nakazima dome test than from the V-bending experiment. It is also observed that through increasing the mesh regularization parameter less damage is predicted in the axial crush simulation.

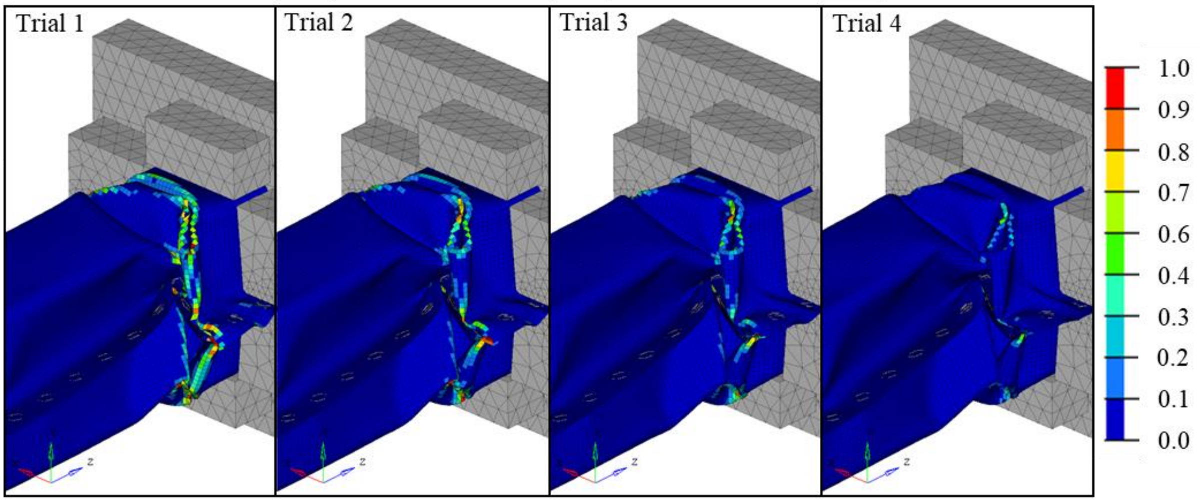

Figure 7. Crush propagation at 6.5 ms after initial impact, showing the elemental integration point average GISSMO damage value in IDH tailored 1000 MPa strength Usibor® 1500-AS for all trials.

Progression of the crash simulation to 16 ms shows all of the trials tend toward a sequential folding pattern along the length of the soft zone (Figure 8), as is observed for the lower strength, more ductile crush tips of Omer *et al.* [10]. It is noted that much larger bend radii are predicted in the 1000 MPa strength material cases than those predicted in Omer *et al.* [10]. The larger bend radii in the folds may be attributed to the higher strength of the 1000 MPa strength cases. As the crash simulation continues past 16 ms fracture is observed in the tight radius folds in Trial 1, whereas Trials 3 and 4 resist fracture in the soft zone.

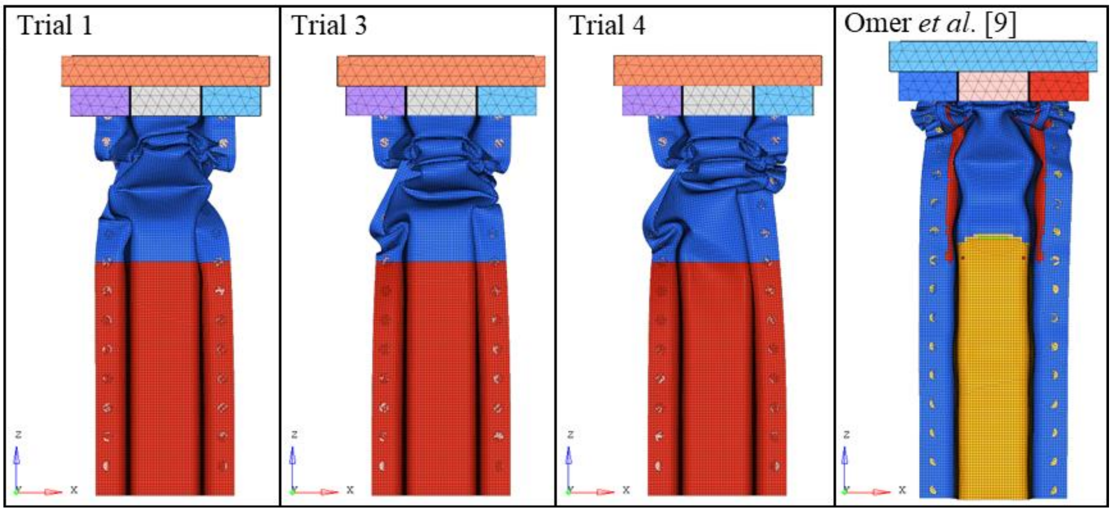

Figure 8. Crush propagation at 16 ms after initial impact, predicts sequential folds in all trials with a larger bend radii than those predicted in Omer *et al.* [10].

The crash energy absorption for the four trials are essentially equivalent up to 200 mm of crush distance, at which point an increase in the energy absorbed in Trials 2, 3 and 4 is noted when compared to Trial 1 (Figure 9). This increase in energy absorption is attributed to the material model's higher resistance to fracture in the soft zone of Trials 2, 3 and 4.

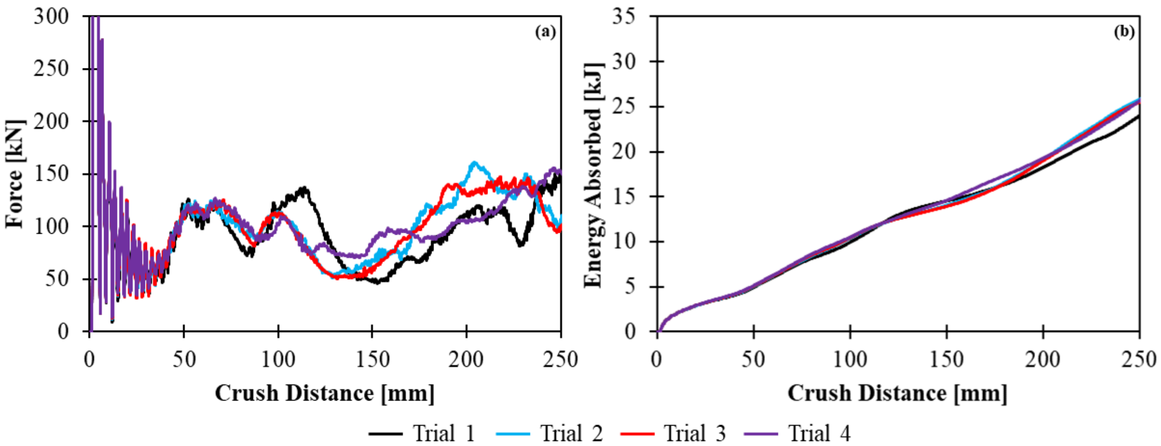

Figure 9. Force (a) and energy absorbed (b) *versus* the crush distance of the axial rails.

5. Discussion and conclusions

The Vickers hardness corresponding to a 1000 MPa tensile strength is predicted to be 317 HV. Experiments by George [2] have shown that this Vickers hardness is achievable through the tailored IDH hot stamping process.

The numerical models of axial crush exhibited a dependency of the onset of fracture upon the adopted plane-strain fracture strain level and degree of mesh regularization. The numerical parametric study comparing the effect of the plane-strain equivalent fracture strains in the fracture *loci* have shown that the plane-strain region Nakazima dome test equivalent fracture strains are more conservative than those of the V-bend test. Current experiments are underway to produce IDH tailored Usibor® 1500-AS rails with tensile strength levels of 1000 MPa. These rails will be tested in axial crush and used to ascertain which plane-strain region test method and regularization parameter more accurately predicts fracture. The crush experiments will also serve to assess the ability of this high strength tailored material condition to undergo axial crush since this cannot be confirmed on the basis of the current model predictions.

In addition to the actual crush experiments, future work will consider introduction of spot weld failure and consideration of forming simulations that can be used to initialize the crush model.

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