Accurate sheet metal forming modeling for cost effective automotive part production

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Abstract. Recent implementations of accurate material and tribology models in finite element codes for sheet metal forming process development have the potential to reduce development time and the associated development costs significantly. Adoption of new models requires validated material parameters and assessments of the overall accuracy. The paper presents a study aimed at accuracy estimation by comparing strain measurements and finite element simulation results for a laboratory flat bottom hole expansion test and an industrial automotive component produced at Volvo Cars. The use of the tensile test based Tata Steel Vegter yield locus model results in accurate prediction of dimensions and plastic deformation distribution in sheet metal forming applications.

1. Introduction
The development and use of cost effective part manufacturing processes can greatly benefit from recent implementations of accurate constitutive material [1, 2] and friction models [3, 4]. The benefit originates in the increased accuracy prediction of material behavior in sheet metal forming by the use of the novel models and can be expressed as substantial reduction of the development time by reducing the need of trial and error iterations and by promoting a first time right approach.

The constitutive material model [1] -- the Vegter yield locus -- and material limit prediction [2] -- the Tata Steel forming limit model -- using only tensile tests data and parameters recently developed at Tata Steel enable a step change in predicting material behavior in sheet metal forming applications. The full benefit of the new models is achieved when a multiparameter model is used for tribology system [5] and by incorporation of realistic industrial process parameters, like actual pressure distribution and process kinematics, as demonstrated in trials on automotive panels at Volvo Cars [3, 4].

In previous work of the authors the material model was established with the aid of additional dedicated tests aimed at predicting work hardening at high strains and the material planar anisotropy. The new model developed by Tata Steel is based exclusively on parameters of the tensile tests and uses empirical relationships for predictions of the rest of the constitutive material behavior.

In this paper the capability of the Tata Steel material model to predict the most important characteristics of a small model test is presented. Geometry and plastic strains measured experimentally and predicted with a finite element model are compared. Finally, effects of the choice of the yield loci (Vegter [1] and Hill48 [6]) on the predictions for a large automotive panel are discussed.
2. Materials, experimental methods and models

A GI coated low carbon steel (VDA239-CR4) with a thickness of 0.7 mm was used for this study. A graphical representation of the material properties are presented in figure 1. The parameters of the models were derived from standard uniaxial tensile testing (ISO 6892-1) as described in [1] and [2]. The strain hardening model is temperature and strain rate dependent, see figure 1. Two yield loci models were generated: the Vegter yield locus according to [1] and the Hill48 yield locus using the AutoForm R7 material generator. The Tata Steel model [2] was used for the forming limit curve (FLC).

The flat hole expansion experiments were performed in a Erichsen press using a flat bottom punch with 100 mm diameter and 10 mm punch radius. The blanks were clamped between a die with 103 mm diameter and 6 mm radius and a serrated blank holder with a blank holder force of 600kN in order to have plastic deformation only in the punch area. Teflon foil and deep drawing oil were used to reduce the friction between the punch and the blank. A hole was punched in the center of the blank with an initial hole diameter of 27 mm. The strains were measured using a digital image correlation technique (GOM – Aramis). The strains were calculated using a grid of 0.5 mm size. The low friction conditions were modeled using a constant coefficient of friction of 0.01. The full experimental geometry was modeled – no symmetry was applied.

For the industrial case strain measurements (GOM – Argus) and finite element modeling were performed on a rear door inner of the Volvo XC90. The strains were measured using a 2 x 2 mm² polka dot grid. The part is formed in a single action press with the die attached to a moving ram, a fixed punch and a hydraulically controlled blank holder (further details can be found in [3] and [4]). The tribology system was modeled using the TriboForm friction model. The model generates a tribocard describing the friction coefficient dependence of contact pressure, sliding velocity, plastic strain and temperature for a given combination of material grade and surface topography, lubricant type and quantity, forming tool type and surface topography parameters. A graphical representation of the input parameters and the friction coefficient dependence on three parameters (at constant temperature) is given in figure 2. In order to take full advantage of the rate dependence effects of material and friction the experimentally measured kinematics of the industrial case is used as illustrated in figure 3. All finite element simulations were performed using AutoForm® plus R7.

3. Results

Figure 4a illustrates the outcome of a typical hole expansion experiment, i.e. the increase of the hole diameter with increasing the punch displacement. In figure 4b the prediction of the finite element model for the experiment from figure 4a for the two yield criteria and the mesh size effects are presented. The model results are presented as relative values – the relative difference in percent between the model prediction and the measured hole diameter. For the Vegter yield locus three mesh sizes were tested as indicated in the figure caption. The deviation of the model increases as the punch displacement increases. The relative deviation is approx. 2% for the Vegter yield locus with the relative fine meshed situations of 1 and 2 mm. The relative coarse mesh of 4 mm predicts remarkably well the experimental hole size evolution. The Hill48 model is significantly less accurate as compared to the Vegter results.

In figure 5 color maps of the thinning patterns are presented at 15 mm punch displacement. Figure 5a shows the results of the on-line strain measurements (the rolling direction is horizontal). Regions of lower thinning close to the edge of the hole are visible in the parallel and perpendicular directions relative to the rolling direction. The highest thinning is measured at the two diagonal directions. This higher thinning regions stretch more than 12 mm away from the edge of the hole. The models with 1 (5b) and 2 mm (5c) size using the Vegter yield locus predicts much better the measured deformation patterns as compared to the 4 mm mesh (5d). 4 mm appears to be too coarse for modeling this experiment. The result with the same mesh size of 2 mm and different yield loci are compared with the experiment in figure 6. The model using Hill48 predicts a much higher deformation localization near the edge of the hole and less thinning in the regions away from the edge.
Figure 1. AutoForm graphical representation of material properties: strain rate and temperature dependent strain hardening (similar for both yield loci models), Vegter (thick line) and Hill48 (thin line) yield loci, FLC.

Figure 2. The elements of the Triboform friction model.

Figure 3. Kinematics of the forming tools for the industrial case.

Figure 4. (a) Experimental hole size evolution as a function of punch displacement and (b) relative prediction deviations of the two yield loci models and the mesh size effects for the Vegter yield locus model.

The measured major and minor strains corresponding to the three sections from figure 6d are represented in figure 7 indicated as “experiment”. The uniaxial deformation paths corresponding to the measured r-values (r0, r45 and r90) are also represented in figure 7. The FLC represents the Tata Steel forming limit of the material. The circular sections are labeled as (1), (2) and respectively (3) in figure 6d and figure 7. The section (1) closest to the hole edge has the highest major strain and the lowest minor
strain values. The sections (2) and (3) represent different minor and major strain combinations respectively. Section (1) is at an initial 1.5 mm distance from the hole edge. The measured strains are already significantly different as compared to the expected theoretical values given by the uniaxial strain path directions. The comparisons with the 2 mm mesh size models with the two yield loci are illustrated separately for the three sections as indicated by the corresponding labels. The model using the Vegter yield locus predicts significantly better the major and minor strain combinations as compared to the model using Hill48 yield locus which systematically overpredicts the strains.

Figure 5. Thinning patterns at 15 mm punch displacement: (a) experiment and Vegter predictions with (b) 1mm, (c) 2 mm and (d) 4 mm mesh sizes. Quarter sections are respectively presented. The color map represents the thinning between 12 and 15%. The hole diameter is approx. 40 mm.

Figure 6. Thinning patterns at 15 mm punch displacement: (a) experiment and model predictions with a mesh of 2 mm using (b) Vegter and (c) Hill48 yield loci respectively. Quarter are respectively presented. The color map represents the thinning between 12 and 15%. The hole diameter is approx. 40 mm. (d) indicates the position of the sections analysed in figure 7.

Figure 7. Measured and model major and minor strain clouds of the three sections from figure 5d: (1) inner section – initial diameter 30 mm, (2) mid section – initial diameter 36 mm and (3) outer section – initial diameter 42 mm. The model strains are extracted from the 2 mm mesh size models for the two yield loci.

The effect of the yield locus model on a relatively large automotive panel is presented in figure 8. The calculated strains usually are represented either as a point cloud (FLD points), where FLD stands for the forming limit diagram, or as a geometrical 3D representation. Typically the predicted formability is color coded with the different colors as indicated in the figure. A contour of the FLD points can be generated as indicated in figure 8 by connecting the maximum equivalent strains for a given set of major and minor strain combinations covering the positive and negative minor strains and the positive major.
strain intervals. The differences between two contours focuses the attention at the maximum predicted strains or thinning. The region 1 in figure 8 illustrates the differences in thinning prediction in the area in the actual part labeled with the same number. The region 2 in figure 8 is composed by the strains near the burster holes in the punch area of the of the part. Region 3 illustrates the difference in the die radius of the part.

![Figure 8](image1.png)

**Figure 8.** AutoForm formability representations and FLD contours for Vegter and Hill48 models. The numbers indicate the regions on the part with large differences in maximum equivalent plastic strain for the two yield loci models.

![Figure 9](image2.png)

**Figure 9.** Blank holder force effect on minimum thickness in area 1 from figure 8. Initial material thickness (0.7 mm) is indicated as $t_0$. The 3D representation illustrates the spatial thickness distribution at 90% relative blank holder force for the Vegter yield locus case.
The effect of the blank holder force on the minimum thickness (region 1 in figure 8) is presented in figure 9. Increase of the blank holder force results in more thinning for both models. However the predicted ranges are significantly different for the two yield loci. The model using Hill48 predicts less thinning as compared to the model using the Vegter yield locus. The differences are practically similar over the entire relative blank holder force range considered and are of the order of 30% relative blank holder force.

The differences in the strains and the corresponding thicknesses at the areas near the edges of the burster holes predicted in the case of the two models are also significant. As an example of such differences the 3D thickness distribution and the strains at the edge of one burster hole is presented in figure 10. The magnitude of thinning and the thickness variation when using the Vegter yield locus is much higher as compared to the situation when the Hill48 yield locus is used.

![Figure 10](image)

**Figure 10.** Thickness distributions in the areas near one of the burster holes (indicated as 2 in figure 8) and the FLD at the edges of the hole for the two yield locus models.

![Figure 11](image)

**Figure 11.** (a) Example of 3D thickness distribution prediction in the area of the large burster hole in figure 8 using the Vegter yield locus. (b) the thickness distribution along a circular section compared to experimental strain results (the arrow in (a) indicates the origin and direction of the section in (b)).

An example of the accuracy obtained by combining the Tata Steel material model and TriboFrom friction models is illustrated in figure 11. The predicted deformation pattern in the large burster hole from figure 8 is presented in figure 11a. An example of good agreement for the thinning localization
distribution along a circular section between the model and the strain measurements is presented in figure 11b.

4. Discussion
The accuracy of a yield locus model formulation and the corresponding finite element implementation can be assessed by studying various deformation modes of anisotropic materials. The sheet metals used in metal forming show various degrees of anisotropy resulting in well-known phenomena like deviations from perfect circularity (earing in cylindrical deep drawing or shape change of circular holes). The CR4 material used in this study has a significant anisotropy, the strain paths are distinct in uniaxial test along various directions like the ones along, perpendicular and at 45° relative to the rolling direction. Both Vegter and Hill48 AutoForm implementations accurately predict the strain paths in simple uniaxial simulations. The difference between the two yield loci becomes evident in more complex simulations where more deformation modes are involved like for instance the hole expansion test presented in this paper. The study of reduced size model tests like this, is very important in assessing the added value of improved models describing material behavior. A reduced size test allows studies of mesh size dependence effects and the test conditions can be much more easily controlled as compared to industrial conditions.

The steel sheet metal deformed in a predominantly plane stress experiment like the hole expansion presented in this paper develops relatively high spatial deformation gradients. The strains vary significantly over distances of the order of 10 mm. A mesh size of 2 mm appears to be sufficiently fine in order to capture the main characteristics of such deformation patterns. Reducing the mesh to 1 mm does not increase significantly the model accuracy while the model size and the simulation time both increases by a factor 4. The 80 and 40 elements along the 27 mm diameter initial hole size for the 1 and respectively 2 mm mesh sizes describe the geometrical characteristics of the experiment sufficiently accurate. It is remarkable to see that the coarser 4 mm mesh is capable of describing the edge geometry evolution, i.e. the hole size diameter increase, very accurately. The coarse mesh however has a significantly lower accuracy in describing the experimentally measured deformation patterns.

For the model test the use of 1 mm mesh size is still feasible. The total number of elements is 100000 and the total computation time is about one hour but such a fine mesh cannot be used for simulations of automotive components as it will result in an unfeasible computation time of the order of weeks. The strategy for simulations of automotive components is to use a relatively coarse initial mesh and to allow mesh refinement. For the example in this paper the initial mesh size is 10 mm resulting in a 50000 initial number of elements and increases to 1 million elements in the final simulation increment. The algorithms controlling the mesh refinement are usually geometry based, i.e. the mesh gets refined when the sheet is bent over tool radii and consequently the mesh is not refined in the geometrically flat areas. At the burster holes there is practically no mesh refinement and the mesh size in those areas remains practically the same, 10 mm. A relative coarse mesh and the choice of the yield locus model might hide potentially high deformation localization and the corresponding high strains in the real automotive panels. The consequence is that cracks at the holes might occur during the initial tests in the tool shop resulting in the need for trial and error iterations for improving the forming safety of the panel.

5. Conclusions
The Vegter yield locus implementation, available in AutoForm R7 as Tata Steel input decks and from R8 in the material generator, provides an accurate description of the steel sheet metal plastic flow anisotropy. The level of accuracy obtained is illustrated in the case of a relatively small model test and a relatively large automotive panel. In the case of the model tests the experimental hole size increase with increasing punch displacement is well predicted. The use of Vegter yield criterion results in a clear accuracy increase compared to Hill48. The differences in accuracy originate from the differences in strain paths (major and minor strains) predicted by the two yield locus models, clearly illustrated by selecting a limited number of elements near the edges of the holes.
The differences found in the case of the industrial example while using the two yield locus models are significant as well. The models predict different forming safety and process control parameter ranges. The study illustrates that choice of the material model has potentially a significant impact on the efforts to identify the parameters for a robust series production process.

Experimental data for the industrial case illustrates the high accuracy offered by the AutoForm implementation of the Vegter yield locus. An increased prediction accuracy has the potential to reduce the number of trial and error iterations needed for setting up sheet metal forming series production processes. The use of accurate models is crucial while considering the options for cost savings and shorter development time as they have the potential to reduce material waste by increasing material utilization and to promote first time right situations.

A successful model based approach can be achieved by combining the state of the art models available in finite element packages like AutoForm and by incorporating realistic process parameters characteristic for the considered series production line. The adoption of new models and the identification of the relevant production line parameters require validation studies on both small and large scale parts. An efficient way of working can be achieved by using the small size tests for assessment of material parameters and for assessing the various options for the finite element strategy use while focusing the studies of the industrial applications on production line parameter identification.

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