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Numerical investigation of cut-edge effect using Gurson-Tvergaard-Needleman model

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Abstract

In this contribution, the formability of sheet metal cut edges is investigated using a damage model. Classical forming limit diagrams are known not to apply properly to the cut edges. However, with mild steels the sheet edges usually behave better than the Forming Limit Diagram predictions, so this phenomenon has not been given sufficient attention. In contrast, for Advanced High Strength Steels the cut edges exhibit reduced formability as compared to the plain sheet; this effect is very sensitive to the quality of the cutting process. The current investigation is aimed to evaluate the ability of available damage models to predict this effect on sample applications. The Gurson-Tvergaard-Needleman model is used and the material parameters for a Dual Phase steel are considered [1]. The effect of the cutting process is described by means of initial fields of equivalent plastic strain and porosity. The geometrical distribution and typical values for these two initial fields are devised based on literature. Numerical simulations of flat notched tensile tests are used within the FE code Abaqus/Explicit to illustrate the impact of the initial fields on the moment and the location of the failure initiation. The influence of the mesh size in the cutting-affected area is also investigated. The hole expansion test and a flat bending test are further simulated to investigate the influence of the cut edge.

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Keywords: Sheet AHSS; Cut edge formability; GTN model; FE process simulation

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1. Introduction

The impact on formability of mechanically cut edges, as compared to machined ones, is an issue that needs to be considered in the case of advanced high strength steels. Indeed, the moment and sometimes even the location of failure occurrence are impacted by this effect. One sample illustration of the phenomenon is provided by the case of bending. If failure occurs when ductile metals are bent over very small radii, the failure usually lays in the middle of the bending line, due to the plane strain loading mode. The bend edge is subject to uniaxial tension, thus has relatively higher ductility and does not fail. The mechanical shearing of the edge induces a loss in ductility, as the material is hardened and damaged in a small area next to the cut. In relative terms, the corresponding amount of ductility loss increases when the material's strength increases, and may lead to failure initiation at the edge (see Fig. 1). The aim of this work was to investigate a numerical model that attempts to take into account the impact of mechanical shearing on the subsequent forming operations.

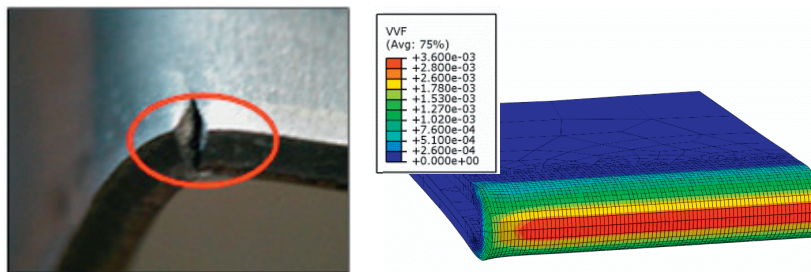


Fig. 1. a) Experimental failure in bending of very high strength steels, starting from the edge. b) Porosity distribution in classical bending simulation.

Very refined models were obtained in the literature by the numerical simulation of the shear process followed by the simulation of the subsequent forming process. The huge computing time and mesh density, along with restrictive remeshing requirements, limit by now this approach to academic investigations on small 2D samples. A more pragmatic viewpoint is adopted in this investigation, where the shearing process is not directly simulated. The geometry of the edge is considered perfectly sharp (see Fig. 2), neglecting the geometrical aspects of cut edges. Along with the specific edge geometry, the cutting process affects the state of the material over a distance comparable to the sheet thickness or less. Effects like material hardening (via hardness tests) and material damage (via local void volume fraction measurements) were clearly identified experimentally and quantified to some extent [2,3,4]. The simplest approach to describe the effect of hardening is through an initial distribution of equivalent plastic strain. This method only allows for the influence on isotropic hardening. The effect on damage can be similarly described by an initial distribution field of a damage variable. In the current investigation, the GTN model is used as available in the Abaqus finite element code, where the damage variable is the void volume fraction or porosity. Distributions of equivalent plastic strain and porosity after shearing were inferred from the literature, as illustrated in Fig. 2.

2. Preliminary investigation of tensile tests on notched samples

The potential of this modeling approach was numerically studied by means of a tensile test on notched sheet samples. Notched tensile samples exhibit plane stress states close to plane strain in the middle of the sample, and uniaxial tensile state at the edges, which mimics the loading modes encountered in bending on a simpler sample configuration. Tensile tests were simulated with and without considering the initial fields of equivalent plastic strain and porosity. A 1.5-mm thick sheet DP600 was considered for the investigation. The material is described by a von Mises yield surface along with isotropic hardening, in the framework of the GTN model. More details on the modeling and material parameters are provided in [1]. Linear hexahedral solid elements are used, with reduced integration.

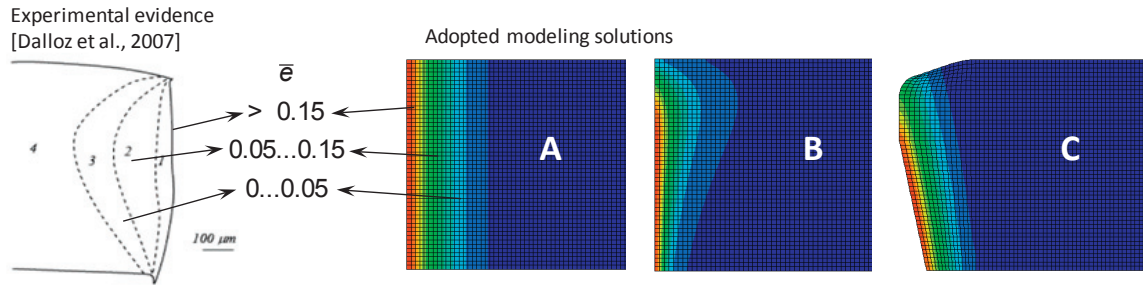


Fig. 2. Examples of simplified geometry description of the cut edge with an initial field of equivalent plastic strain / porosity in the numerical model of the subsequent forming step, inspired from experimental observations in the literature. Three levels of refinement were attempted, in terms of initial geometry and initial distribution of the strain and porosity fields.

Fig. 3 shows the impact of the initial fields due to shearing on the moment and location of failure. Thus taking into account the sheared edge with this method allows for a reasonable description of the main effects. Moreover, even if the dissymmetry of the edge, with a burr on one side, is not described geometrically, its effect is clearly visible thanks to the dissymmetry of the initial fields of strain and porosity.

	Equiv. plastic strain distribution at failure	Porosity distribution at failure	Displacement at fracture	Location of failure
Without initial fields in the cut zone			3 mm	Centre of the specimen
With initial fields in the cut zone (model "B")			0.6 mm	Edge of the specimen ("burr" side)

Fig. 3. Failure predictions for the notched tensile test with (bottom) and without (top) considering initial fields of equivalent plastic strain and porosity.

The adopted simplified geometry of the cut edge allows for significantly coarse meshes as compared to those required to simulate the shear process. Nevertheless, in comparison to the mesh required for the regular simulation of forming processes, a much finer mesh is still required in order to describe accurately the initial fields. In particular, the experimentally observed porosity fields are much localized in the vicinity of the edge, over a penetration distance of a few percent of the sheet thickness. A numerical sensitivity study allowed for an evaluation of the accuracy loss when the element size is increased.

In Fig. 4, the influence of the initial maximum porosity value at the edge on the tensile grip displacement at failure is shown for several values of element size in the in-plane direction normal to the edge. As expected, the mesh density has an influence on the fracture results. For the coarsest meshes, the element size becomes larger than the size of the shear-affected zone and only one single element in a row is affected by the initial distribution of porosity. More conservative results are obtained with coarser meshes, as the failure is predicted earlier. However, Fig. 4 tends to show that the relative impact of the mesh size is much smaller than that of the initial porosity value

imposed at the edge. Although the effect is not negligible, it is clear that its range is significantly smaller than the error range on the initial porosity due to cutting.

For most of the subsequent simulations in the study, an element size of 0.3 was selected. For this element size, Fig. 4 tends to show that the mesh sensitivity becomes negligible. This element size is required for the accurate prediction of the bending process considered hereafter. However, for sheet stamping simulations one would need to adopt even coarser meshes.

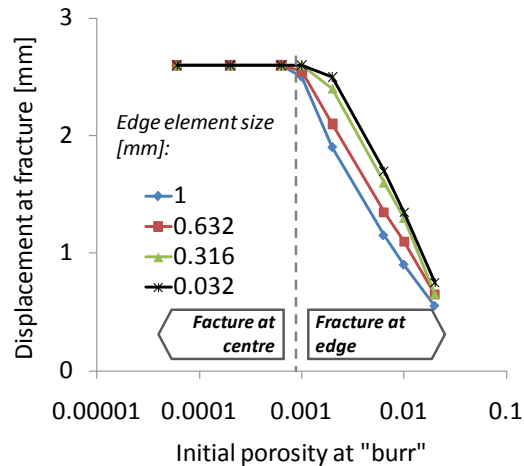


Fig. 4. Mesh sensitivity of the predicted grip displacement at fracture.

3. Impact on failure predictions during hole expansion and bending

The simulation of the hole expansion test with conical punch [5] was used to explore the impact of the shear-affected zone on cut edge failure predictions. Fig. 5 shows the void volume fraction distribution in the edge area for various initial conditions. All the results are reported at the same punch stroke for comparison. When no initial fields (strain and porosity) are considered, a very low level of void volume fraction is attained. This may corroborate with the notoriously high hole expansion ratios that can be reached with carefully machined edges. On the other side, considering the impact of punching leads to significant values of porosity, indicating that at the considered punch stroke the metal would have already failed. The impact of shearing on this particular application appears clearly. The three approaches adopted to model the initial internal variable fields provide very similar results, especially the maximum porosity value and location, confirming that the exact description of the initial distribution is a secondary aspect. Also, various meshes with element size from 0.03 mm (shown in Fig. 5) to 0.3 mm delivered very close results.

The flat bending test proposed by the European Coil Coating Association was further considered, which consists in a free V-bending at an angle smaller than 90° , continued by a flat bending at 0° between two flat surfaces. As already illustrated in Fig. 1b, eight elements are used through the sheet thickness to describe the heterogeneous fields of strain and stress. Several simulations were performed with different descriptions of the cut edge: without initial strain/porosity fields, and with initial fields described by model "B" and oriented in both directions (inward / outward with respect to the bending orientation). Fig. 6 depicts the final distributions of void volume fraction in the three configurations. In this case of bending, the amount of damage is significant on the outer surface of the bending line, especially over its central zone (relatively far from the edge). As expected, the use of the shear-induced initial fields increases the void volume fraction at the edge. At the end of such an extreme bending, the porosity on the outer surface takes two local minima: one along the plain-strain region along the bending line, and a new one at the edge, which was not revealed by the classical simulation without initial fields. The location of the global maximum value, and its criticality (e.g., with respect to failure by coalescence) depend on the shear-induced

initial values. The orientation of the “burr” (on the inner or outer surface with respect to the bending direction) also significantly influences the result, as experimentally observed in the literature. With the material parameters identified in [1], failure would occur in the central zone with ideal (machined) edges, while it will occur at the edge when the cut edge is considered, with the outward-oriented burr. In the case of an inward-oriented burr, the predictions suggest that the failure risk is almost equivalent in the two zones.

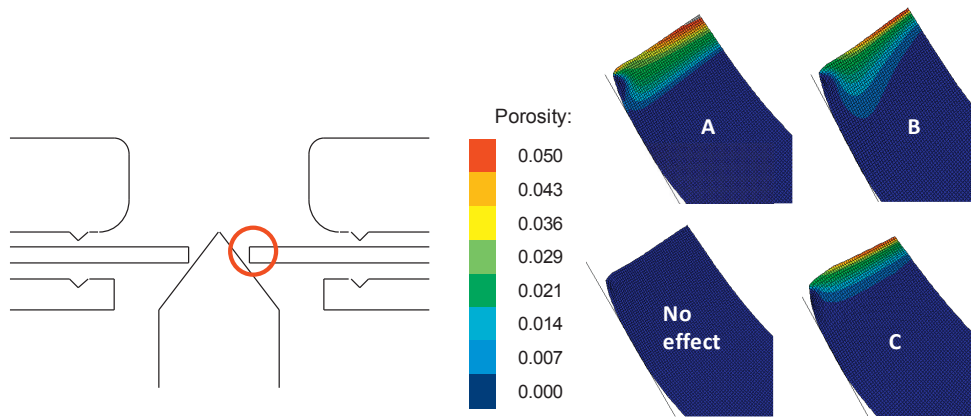


Fig. 5. Sketch of the hole expansion test (left) and distribution of void volume fraction at an imposed punch stroke (left), with and without considering initial fields induced by the hole punching.

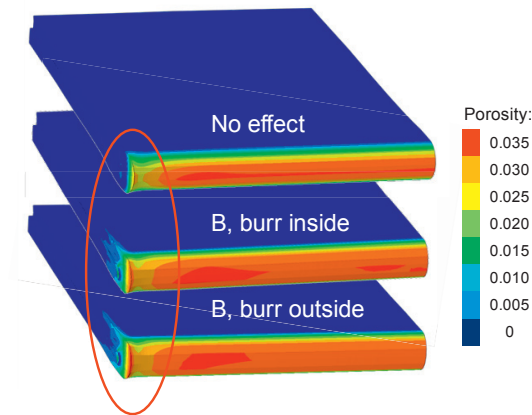


Fig. 6. Distribution of void volume fraction at the end of flat bending, with and without considering initial strain and porosity fields induced by shearing.

4. Conclusions

In this numerical investigation, the effect of the shear-affected zone on the residual formability of sheet steels was described through the initial fields of equivalent plastic strain and void volume fraction in the neighborhood of the sheared/punched edge. The investigation revealed that considering the initial porosity at the edge has the most important impact, and especially the maximum porosity value at the edge. Comparatively, the actual description of

the porosity field in the sheared-affected zone is secondary. Taking or not into consideration the initial field of plastic strain also showed no impact on the failure predictions – although it should be considered for physical consistency. An equally important observation concerns the mesh refinement required to accurately take these effects into account. It appears from the investigation that the required mesh can be much coarser than the ones needed, e.g., to accurately predict the shearing process. Even with the mesh density usually adopted for the regular forming simulations, sufficiently relevant results are expected for industrial application.

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