

An Approach to Model Sheet Failure After Onset of Localized Necking in Industrial High Strength Steel Stamping and Crash Simulations

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ABSTRACT

In large-scale industrial simulations the numerical prediction of fracture in sheet metal forming operations as well as in crash events is still a challenging task of high social and economic relevance. Among several approaches presented in literature, the authors and their colleagues developed a model which accounts each for three different mechanisms leading finally to fracture in thin sheet metals: the local instability (necking), ductile normal fracture and ductile shear fracture. The focus of this paper is to develop and validate a new approach to improve the predictive capabilities for fracture triggered by localized necking for a wide variety of steel grades. It is well known that after the onset of a local instability additional strain is still necessary to induce fracture. In a numerical simulation using shell elements this *post instability strain* becomes of increasing importance when the ratio of the characteristic shell element edge length to its thickness decreases. Today's shell element lengths in industrial applications can be of the same order as the width of the necking zone. Therefore, the *post instability strain* may contribute to a significant percentage of the shell elements total elongation up to fracture and cannot be neglected any longer.

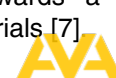
The enhanced necking model termed Post Instability Strain Model for Shells (PIS Model) combines the model for localized necking with the model for ductile shear fracture. Guided by careful Nakajima type tests of three representative steel grades, the development of the PIS Model also focuses on minimizing the influence of varying shell element edge lengths. The model is implemented in such a way that the elongation of a shell

element after onset of necking is highly independent of the element edge length.

The improvements achieved with this model are demonstrated by validation examples which include small specimens (tensile specimen with circular hole), technological sheet metal forming experiments (Nakajima tests) and finally the 3-point bending test of an automotive component.

INTRODUCTION

Localized necking is the dominant mechanism leading to fracture in sheet metal forming and crash. A material model should be used which allows a reliable prediction of the onset of localized necking. A conventional approach is the use of the so called Forming Limit Curve (FLC) which is, however, limited to linear strain paths and does only represent the onset of localised necking and not the strain at material fracture. Furthermore, in the case of arbitrary strain paths theoretical algorithms have to be used for failure prediction. In 2001 the authors already validated the algorithm Crach for this purpose [1]. At that time the typical mesh size for shell elements in crash simulations was approximately 10 times the sheet thickness. As the localized neck has a typical width of one sheet thickness the additional strain from the onset of necking up to final fracture is comparatively small. Therefore the onset of necking was used as an elimination criterion for the critical elements. Later criteria for ductile shear fracture and ductile normal fracture have been added towards a comprehensive failure model for metallic materials [7].



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This comprehensive failure model has been applied in [2] to support the material selection for a side intrusion beam under impact loading. In [2] the correspondence of failure prediction and experimentally determined intrusion until rupture was quite promising. However following investigations also showed significant discrepancies for different design and load conditions where localised necking was the relevant criterion. Figure 1 shows the impact force versus punch intrusion for the 3-point bending test of a side intrusion beam (see also Figure 14) from experiment and simulation. In this simulation the onset of localized necking was used as an element elimination criterion. This simulation technique resulted in a very conservative prediction of the possible punch displacement up to fracture (approx. 25 mm). In reality the side intrusion beams did not fail up to a punch displacement of 80 mm.

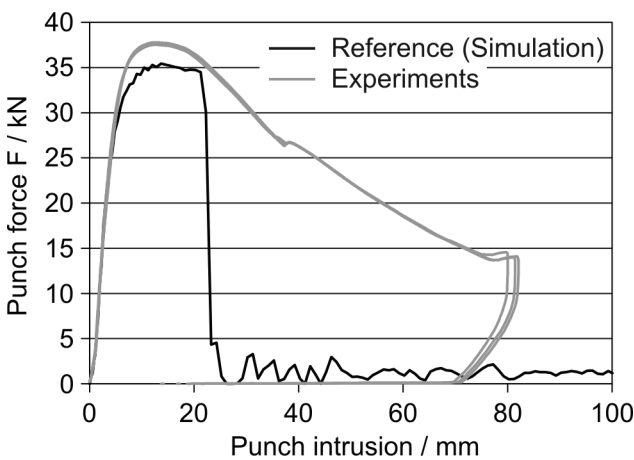


Figure 1. Simulated and experimentally measured force vs. intrusion for a three point bending of a side impact beam made of an ultra high strength steel grade

In the tested specimens multiple localized necks have been observed whereas in the simulation only one row of elements became critical due to localized necking. The problem became even more severe when refined shell meshes were used. Today typical mesh sizes approach even the same order of magnitude as the element thickness. Therefore the additional strain from onset of localized necking up to final fracture can cover a significant percentage of the elements' total elongation. This additional strain may have a significant influence when predicting the final fracture of a sheet metal caused by either shear or ductile fracture. Consequently it provides the motivation to develop an enhanced failure model for shell elements which combines the existing model for localized necking with the criteria for ductile normal fracture and ductile shear fracture. As the inhomogeneous strain in the growing neck cannot be resolved with a shell element, a suitable auxiliary model has to be developed. This auxiliary model should work in such a way that the strain after onset of necking is highly independent of the shell element edge length.

In the following the work of a common research project of the BMW Group, ThyssenKrupp Steel (TKS) and Matfem is presented. The focus of the work is the validation of a new approach for the modeling of the additional strain after onset of localized necking in shell elements (PIS = Post Instability Strain Model for Shells) for a wide variety of steel grades.

First the material characteristics of different steel grades are discussed. Later the idea of the model will be presented and demonstrated for applications ranging from laboratory specimens up to real automotive components.

MATERIAL CHARACTERISTICS

To fulfill the increasing demands for light weight construction in combination with outstanding crash performance the steel industry is developing more and more different grades. As a result of this process, the automotive engineer today is facing a large variety of different steel grades with ultimate tensile strength from 290 MPa up to 1600 MPa. Figure 2 gives an example of different hardening characteristics and mechanical properties for a selection of steel grades, partly also used in the following investigations. The MHZ340 from TKS is a conventional microalloyed steel grade (HSLA) with fine globular microstructure containing Ti and / or Nb carbonitride precipitations. From the families of multiphase steels the dual phase DP-K 34/60 shows a low yield stress in combination with a high ultimate tensile strength. The microstructure consists mainly of a soft ferritic matrix with islands of a second, hard, mainly martensitic phase. The soft ferrite accounts for up to 90% of the microstructure. A next step to more pronounced hardening is the retained-austenite (TRIP (transformation induced plasticity) steel) RA-K 40/70 [3]. Here the retained austenite is transformed to martensite during forming operations. As delivered the retained-austenite is embedded in a ferrite / bainite matrix. Small amounts of martensite may also be present. The phase transformation results in a balanced hardening and allows high amounts of stretch forming operations. Finally the complex phase steel CP-K 60/78 is a further representative of steel development. The extremely fine microstructure is a balance of ferrite, bainite, martensite and precipitation of hardening phases in the microstructure which provide a particularly attractive application profile.

HARDENING POTENTIAL – Looking at the given tensile test values in Figure 2 for uniform elongation, total elongation in combination with the n-value the different performance of these steel grades becomes obvious. Even in the yield stress around 400 MPa there is quite a choice of different grades to fulfill the requirements of e.g. automotive components. In this context it has to be mentioned that beside the cold rolled grades presented here the same grades are available as hot rolled steels.

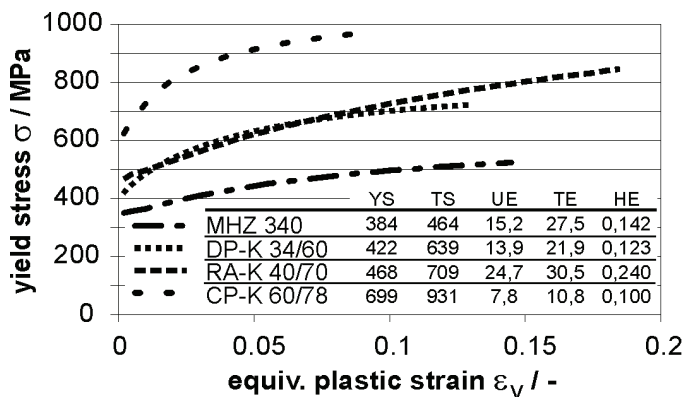


Figure 2. Yield curves in RD and tensile properties for different cold rolled steel grades in TD

The different characteristics of material yield curves denote the material potential in forming and crash operations. In forming, the modern multiphase steels allow a good cold forming ability compared to the material strength. Therefore these material grades are often used in complex structural parts for the automotive body. In figure 3 the energy absorption for two different load cases is shown for the materials investigated here. The tests, performed under static load conditions are

- A three-point-bending test of a rectangular, closed profile with a closing plate. The width of the section is 60 mm, whereas the height is only 30 mm.
- An axial crush of a flangeless square profile. The typical dimension of 60 x 60 mm for the section has been used in combination with a height of 300 mm. By robust and stable wrinkling the test setup allows a good ability for characterizing the energy absorption of different material grades.

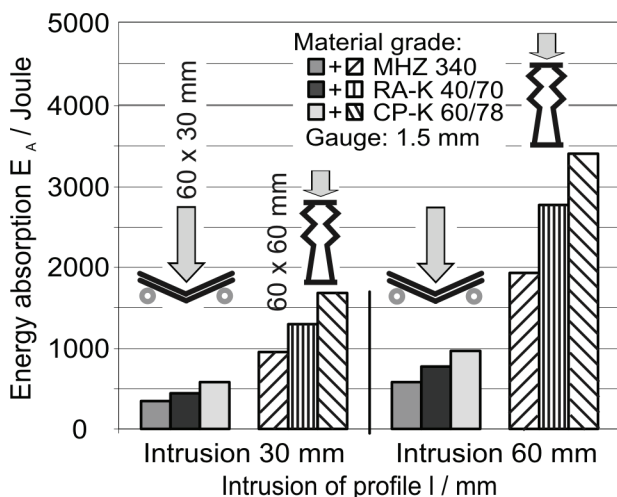


Figure 3. Energy consumption of different cold rolled high strength material grades in static tests (bending and axial)

All materials were of standard thickness at 1.5 mm. For the intrusions of 30 mm and 60 mm the energy consumed were calculated from the measured force – punch intrusion diagrams respectively. It can be said that

with increasing tensile strength the material allows higher energy consumption in both load cases. Of course we have to keep in mind that higher strength material often shows lower ductility, reduced residual forming potential and / or a more severe sensitivity to cut edge cracking. Therefore for the development of components, the best compromise of shape, material forming and crash performance must be found.

For the steel grades shown the appearance of significant failure is not expected under the load conditions and intrusions shown below. In contrast the energy absorption of higher strength materials can be significantly influenced by increasing appearance of failure.

FAILURE CHARACTERISTICS – The still dominant failure in sheet metal forming or crash deformation is a localized neck followed by a fracture. The amount of strain a material can sustain from the onset of instability up to the moment of local fracture by cracking can be an important parameter for industrial application. In sheet metal forming simulations this effect may explain why some critical forming operations can be performed in reality without fracture although the FLC criterion already indicates failure. In crash simulations the use of the post instability strain leads to a less conservative prediction of the onset of a component failure. Besides a failure by localized necking (followed by fracture) we can also notice some cracks due to ductile shear fracture for high strength material without prior necking. Therefore the criteria for ductile normal fracture and especially ductile shear fracture must be monitored parallel to the criterion for localized necking when operating with high strength steel grades.

Figure 4 shows examples of the experimentally measured curves for instability and shear fracture for the given materials. From the level of forming limit curve the microalloyed steel MHZ 340 shows the best forming potential, followed by the TRIP and complex-phase steels. The corresponding, experimentally determined points for shear fracture strains have been recalculated into continuous failure curves based on the formulations in [2]. The ranking in forming potential for this failure mode is given by MHZ 340 followed by CP-K 60/78 and finally the TRIP RA-K 40/70. Compared to the microalloyed steel the multiphase steels react more sensitively to shear failure.

To establish a basis for modeling of the material behavior after onset of localized necking, fundamental experimental investigations were carried out. In order to analyze the possible values of strains and elongations from start of localized necking up to material failure (referred to as “post instability strain”), at first conventional FLC experiments were carried out. Nakajima tools according to the setup of the new ISO 12004 proposal were used.