INFLUENCE OF MANUFACTURING PROCESSES ON THE PERFORMANCE OF VEHICLES IN FRONTAL CRASH

EINFLUß DES FERTIGUNGSPROZESSES AUF DIE CRASHEIGEN-SCHAFTEN EINES PERSONENKRAFTWAGENS BEIM FRONTALAUFPRALL

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Abstract

The importance of new material applications for improved passive vehicle safety is increasing. Automotive companies are using CAE methods to predict the crash behaviour of cars and to select materials for body structures, which fulfill the safety targets. The quality of crash simulations heavily depends on the material models used for these investigations. In this paper results of research projects on the application of new high strength steel sheet metal in side rail structures are presented. The simulation models used in these studies are described and their importance for Finite Element applications in passive safety is underlined.

Zusammenfassung

Der Einsatz neue Werkstoffe zur Verbesserung der passiven Sicherheit von Fahrzeugen gewinnt zunehmend an Bedeutung. Zu beachten ist hierbei, daß in allen Unternehmen der Automobilindustrie die Vorhersagen von Crashereignissen mit Hilfe von CAE-Methoden einen wichtigen Stellenwert einnehmen und mittlerweile unverzichtbar für die Auswahl geeigneter neuer Werkstoffe für Karosseriestrukturen sind. Die Güte der Simulationen hängt dabei maßgeblich von den eingesetzten Simulationsmethoden ab. Es werden die Ergebnisse von Forschungsprojekten vorgestellt, die sich mit dem Einsatz von neuen höherfesten Stahlblechen für Längsträgerstrukturen beschäftigen. Die eingesetzten Simulationsmodelle werden erläutert und belegen die besondere Bedeutung, die diesem Kapitel der Finite Elemente Crashanalyse – auch in Zukunft – beizumessen ist.

Introduction

The reduction of the cycle time in vehicle development in conjunction with an increasing demand for passive safety features leads to a significant involvement of CAE methods to predict the crash performance of cars. In early design phases the Finite Element (FE) models are used for concept studies. Based on the results of these studies, component or substructure tests give beneficial input for the final FE vehicle model including all the design proposals which need to be verified in this full vehicle CAE analysis.

For the optimization of the structural behaviour of car bodies under a variety of crash impact conditions several trade-offs occur which are solved within iterative CAE processes. Taking frontal impact as an example, the side rail reinforcement of the Ford Focus was designed considering both high and low speed impact (insurance test) requirements [1,2,10].

In order to meet the stringent development timing it is prerequisite that the material suppliers, who are involved early in the development, support the CAE investigations by providing the material parameters needed for the crash analyses. National and international project teams are currently developing material databases for different types of materials. These databases should include crash relevant material properties which can be used to describe the material behaviour under impact conditions with different velocities. The material parameters are related to the constitutive models used in FE crash calculations with explicit codes, like RADIOSS, LS-DYNA or PAMCRASH.

New steel sheet metal grades, e.g. DP (Dual Phase), TRIP (TRansformation Induced Plasticity) and TWIP (TWinning Induced Plasticity) steels, used for body parts give the opportunity to reduce weight and increase energy absorption capabilities of structures. An example of a front side rail part made of DP steel shows the importance of including work hardening and gauge reduction effects due to the stamping process in crash FE analyses.

Advanced High Strength Steel in Body Structures

General Aspects

State of the art is the use of High Strength Low Alloyed Steels (HSLA) for crash-relevant body parts. For example, for the front side members of the Ford Focus the HSLA steel "ZStE340" is used. Typical micro-alloying elements are Titanium, Niobium and Vanadium. The main strengthening mechanisms of HSLA steels are grain refining and precipitation hardening. One disadvantage of HSLA steels is their decreasing ductility with increasing strength. Therefore, a key development goal for new steels is to increase the strength without further compromising the ductility. Examples for these efforts are the upcoming Dual Phase ("DP") and Transformation Induced Plasticity ("TRIP") steels.

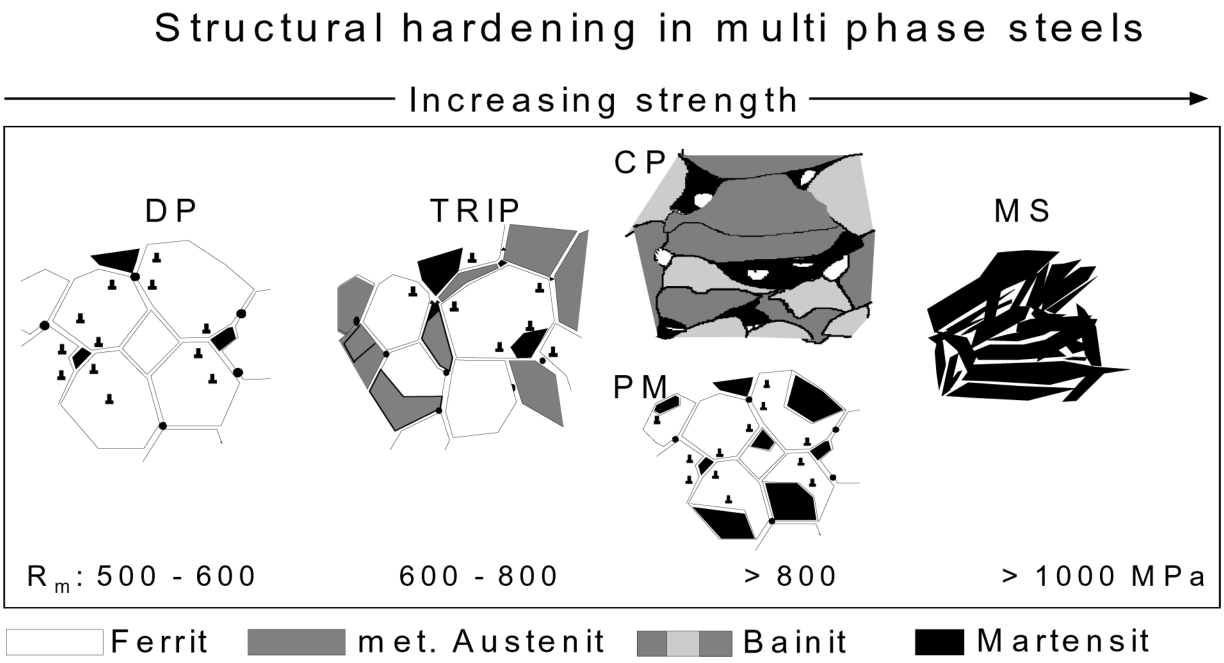


Fig.1: Metallurgical aspects of DP and TRIP steels [3]

For these steels the strengthening is achieved by introducing hard phases next to softer ones. DP steels have martensitic grains embedded into a ferritic matrix, Fig. 1, [3]. The portion of the martensitic grains is up to 20 vol.%. The microstructure of TRIP steels consists of a ferritic/bainitic matrix and metastable austenitic grains, Fig. 1. These austenitic grains transform into martensite during deformation, leading to an additional hardening of the material.

The naming of HSLA steels is based on their minimum yield strength. For example, a ZStE340 has the yield strength of at least 340MPa. In contrast to this, the names of Dual Phase and TRIP steels indicate the Ultimate Tensile Strength (UTS), e.g. for the TRIP700 the UTS is > 700 MPa. A renaming of these steels, also based on the minimum yield strength, is at the moment under discussion.

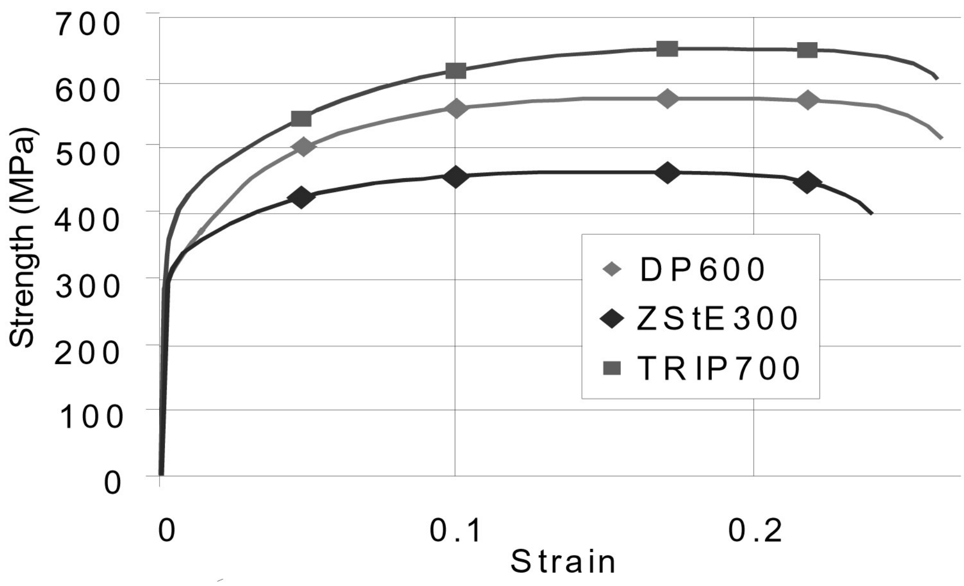


Fig. 2: Engineering stress-strain curves of DP600, TRIP700 and ZStE300 steel

Steel	YS $R_{p0.2}$ / MPa	UTS R_m / MPa	ε_{fr} / %	n_{4-6}-value
FeP04	175	290	> 40	0.22
ZSTE300	330	430	>22	0.17
ZSTE420	480	530	>16	0.11
DP600	390	600	>20	0.18
TRIP700	420	700	>24	0.20

Tab. 1: Mechanical properties of different steels

Characteristic for DP and TRIP steels is the very high ultimate tensile strength in relation to their yield strength. This is demonstrated in Fig. 2 and Tab. 1. Fig. 2 shows stress strain plots for the DP600 and the TRIP700 in comparison to the HSLA steel ZStE300. In Tab. 1 the mechanical properties of DP and TRIP steels are compared with HSLA and mild steels. The yield strength of the DP600 is similar to that of the ZStE300 but its ultimate tensile strength is remarkably higher. The same behaviour is detected if the TRIP700 is compared with the ZStE420: although the yield strength of the TRIP700 is about 60 MPa lower than that of the ZStE420, its ultimate tensile strength is 170 MPa higher. In addition to their high strength levels TRIP and DP steels possess a good ductility. Their uniform and fracture elongations are higher than those of HSLA steels of lower strength. The strong work hardening, represented by high n-values, leads to a good stretch bending behaviour. In contrast to this, increasing the strength of HSLA steels leads to a drastic reduced n-value.

The good stretch bending behaviour of DP steels was demonstrated by the stamping of a front side member reinforcement of a Ford vehicle which is currently in production: in an area, where mainly stretch bending is applied, a thinning of initially 2.00 mm sheet thickness to 1.55 mm after forming of the ZStE300 part occurred. This thinning was limited to 1.70 mm for the DP600 material. In addition, the strong work hardening of DP and TRIP steels leads to an increased material strength in the formed part.

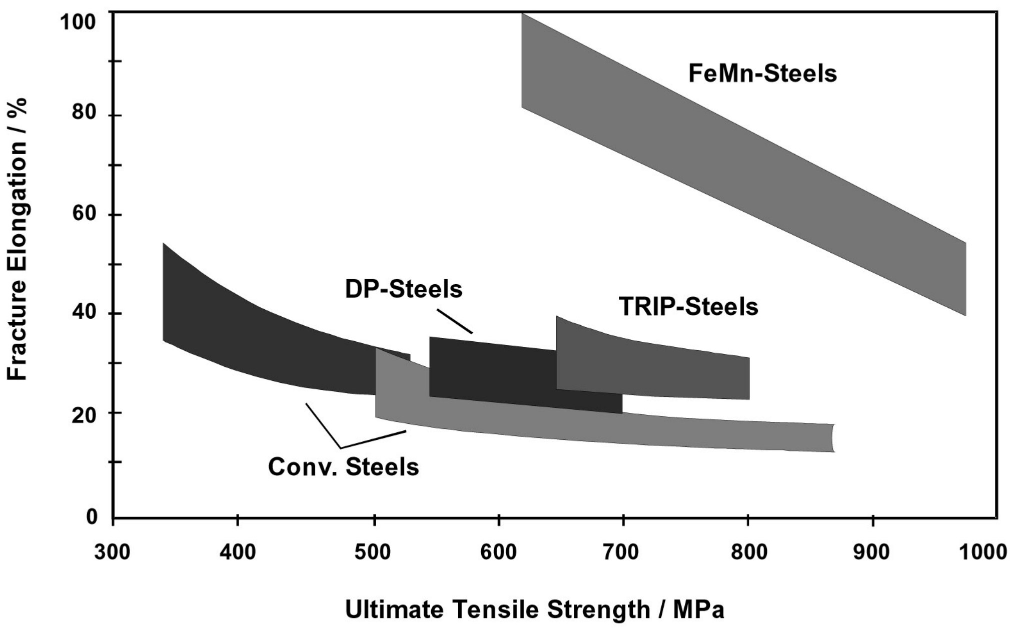


Fig. 3: Fracture elongation versus ultimate tensile strength of different steels

Steels with reduced density are under development. Most promising are FeMn steels with Manganese contents of 15-25 wt.% and additions of Aluminum and Silicium [4]. The density $\rho = 7.3$ g/cm^3 of these steels is about 6 % lower than that of standard steels. In addition, these steels combine high strength with excellent ductility.

FeMn steels with about 15 wt.% Manganese possess an austenitic/ferritic matrix with a martensite content of about 10%. The high strength is due to the hard martensite phase and solid solution hardening by Manganese. These steels are TRIP steels, this means the austenite transforms to martensite during deformation. This strengthens the material further and leads to the good ductility. The yield strength of the Fe15Mn3Al3Si steel is 430 MPa, its ultimate tensile strength 870 MPa. For this high strength level it has a remarkably good ductility represented in the fracture elongation $\varepsilon_{fr} = 45$ %.

FeMn steels with about 25 wt.% Manganese are pure austenites. Also after cold deformation the microstructure is unchanged. They possess an excellent ductility due to strain induced twinning. Therefore they are named TWIP (Twinning Induced Plasticity) steels. The fracture elongation of the Fe25Mn3Al3Si is 95 % and therefore higher than that of a mild steel. But its strength of YS = 230 MPa and UTS = 620 MPa is superior (compare with Tab. 1). In Fig. 3 the fracture elongation versus ultimate tensile strength for conventional, DP, TRIP and FeMn (TRIP and TWIP) steels is plotted. It is visible that DP and TRIP steel have a favourable combination of high strength and good ductility; but they are clearly outperformed by FeMn steels.

Crash Simulation of Stamped Body Parts

A world wide survey on the application of Advanced High Strength Steels underlines the direction of improved crash energy management, in Europe and Japan in particular, with a significant increase of DP and TRIP steel implementation in body structures [5]. The most important advantage of these steel grades is the improved formability compared to standard high strength steels, which allows the design of more complex parts with an improved crash performance. The significant work-hardening behaviour during the plastic deformation compared, for example, to standard micro-alloyed steels leads to the necessity to consider the stamping effects on the material characteristics as well as the gauge reduction of the sheet metal parts in crash simulations.

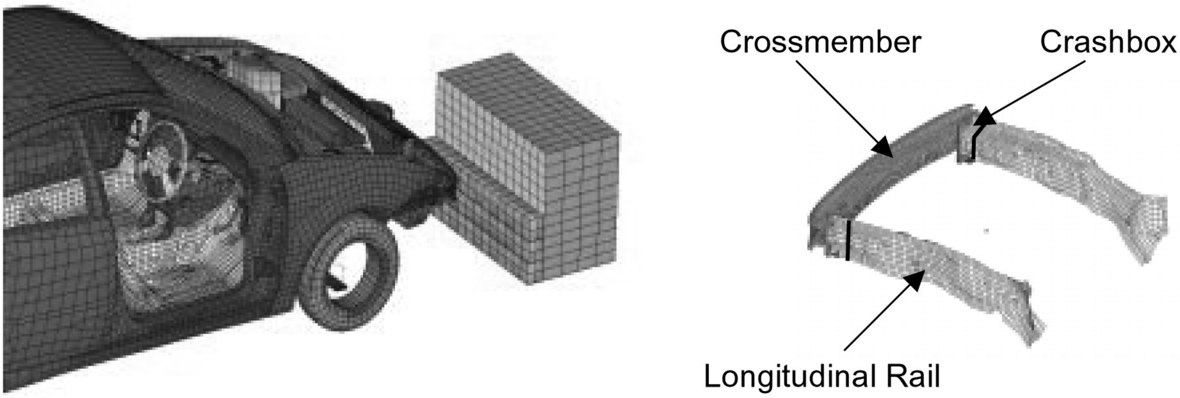


Fig. 4: Finite Element Model of a front end substructure with side rail

Several investigations were carried out in the past to quantify these effects on the crash behaviour of different body components [6, 7, 8]. The outcome of these studies was that the sheet metal forming process influences the crash characteristics of longitudinal body members in such a way that the energy absorption is higher and the body component stiffer with an increased maximum force level of 8 – 25 %.

In 1997 several CAE studies have been performed in co-operation with the Universities of Cottbus and Dortmund [9]. The objective of this research project was to determine the importance of the consideration of manufacturing processes on plastic deformation and energy absorption of crash relevant body components as well as to identify the ability to combine metal forming and crash simulation with the FE codes used at Ford. Three different steels, one mild steel FeP04 and two high strength steels (ZStE220BH and DP500), were studied using the explicit FE code LS-DYNA to simulate the stamping process including springback after forming and the crash process of a simple U-shaped profile under axial loading. Structures with U-shaped cross sections are often used as side rail components in the front end of a vehicle, Fig. 4.

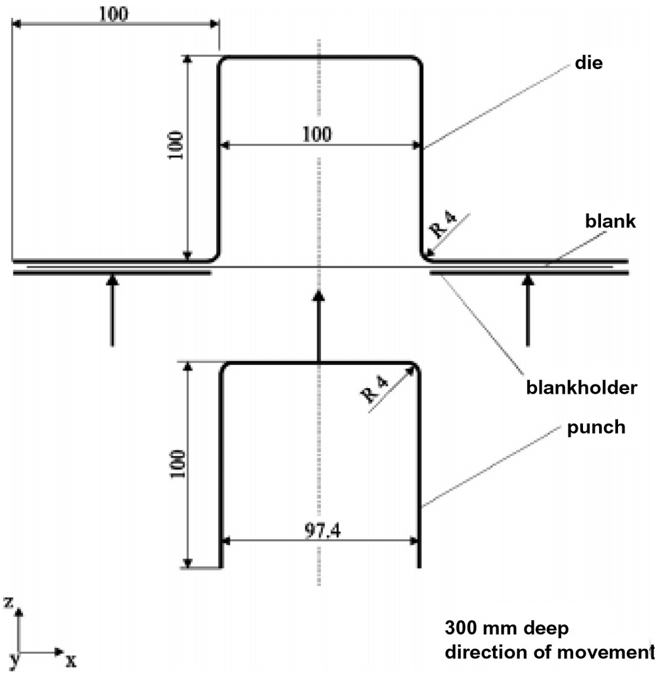


Fig. 5: Tool geometry for stamping simulation of an U-shaped profile

The following paragraph describes the models used in this study and the main results. Fig. 5 sketches the dimensions of the tool geometry for the stamping simulation. Half of the blank (sheet metal gage 1 mm) is modeled with 27000 Belytschko-Wong-Chiang shell elements with an element size of 1 mm taking into account the symmetrical aspects of the problem. Piecewise linear flow curves (true stress – true plastic strain curves) are used to describe the elastic-plastic behaviour of the sheet metal. The experimental determined curves are extrapolated in a non-linear way. After the stamping simulation with a punch displacement of 49 mm (U-profile depth 50 mm) and a constant blankholder force of 125 kN a springback calculation is added using the small restart option in which the interface definitions between workpiece and rigid tools are deleted.

The full restart option is used to transfer the results – including thickness distribution, strains and residual stresses – to the crash simulation and change the contact definitions. To create a closed side rail section, a filler plate is added. This plate is designed with swages to trigger the folding process during the axial compression of this column. Important for the material description is the consideration of strain rate parameters to model the dynamic behaviour of the sheet metal. Strain-rate dependent flow curves deliver the required input for the model.

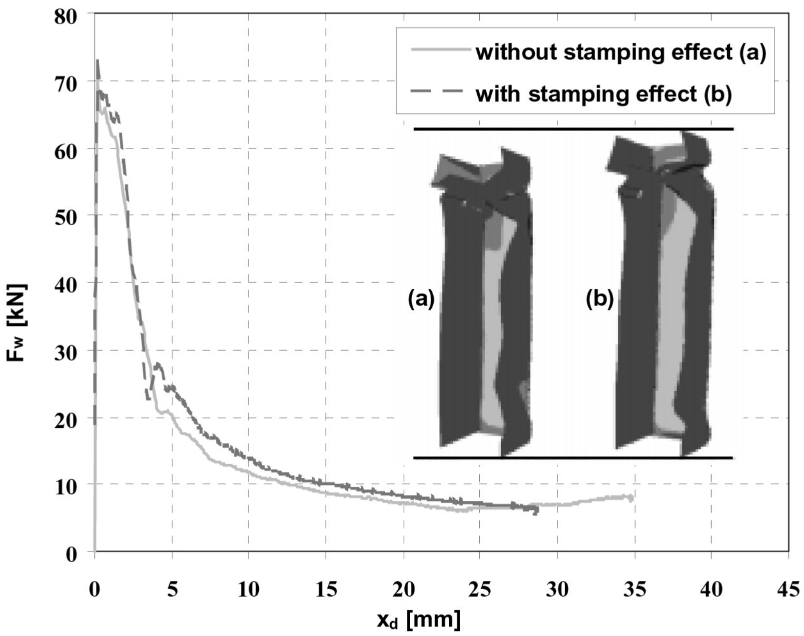


Fig. 6: Force-deflection curve with and without stamping effects - DP500

DP500	Model without stamping effect*)	Model with stamping effect	Difference
Deformation x_d	34,8 mm	28,7 mm	-17.5%
Peak Force $F_{w,max}$	71,7 kN	75,3 kN	5.0%
Mean Force $F_{w,mean}$	10,2 kN	10,8 kN	6.1%
Time $t_{Ei=max}$	6,7 ms	6,3 ms	-7.0%

*) 100%

Tab. 2: Summary of results - DP500: $F_{w, mean}$ is the average force for: max , $10 \le x_d \le x_{d,max}$

The crash behaviour of the various steel (FeP04, ZStE220BH, DP500) longitudinal member is remarkably different. The highest influence is observed in combination with the DP500 material. In Fig. 8 the calculated force-deflection curves and the deformed structures are plotted. The model with stamping effect is stiffer, the total deformation smaller (-17,5 %) andthe force level about 5 - 6 % higher, Tab. 2.

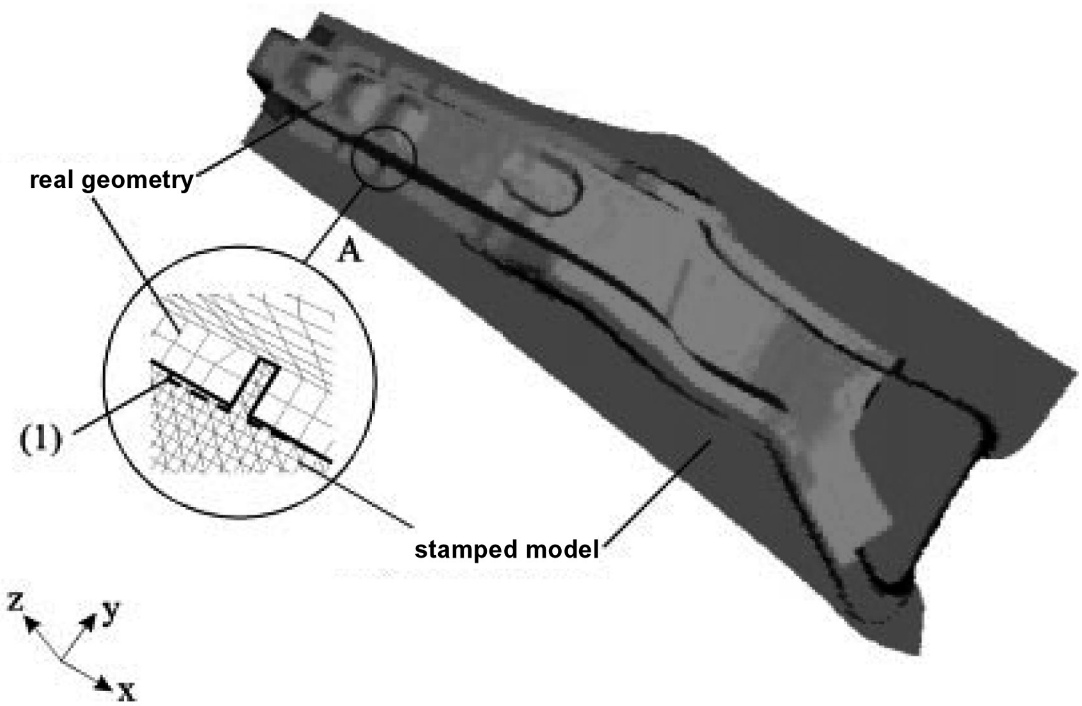


Fig. 7: Comparison of stamped panel and side rail design geometry

The presented method to combine stamping and crash simulation is not applicable in the current CAE driven crash development process. The usage of small elements and a fine mesh for the crash analysis lead to a reduction of the time step which affects directly the turnaround time of the crash simulations. In the daily business of crash analysis this is not applicable. On the other hand, the stamping CAE analysts use different FE codes for their studies with different meshes, element types, material models, including adaptive mesh refinement algorithm during the simulation of the stamping process which do not connect well to the explicit codes used for crash analysis.

Fig. 7 shows the different geometry and mesh between the stamped part and real side rail geometry implemented in the full vehicle model for crash analyses. This figure points out that mapping algorithms are required to couple both types of simulations. Therefore, a working group of the Research Association of the German Automotive Industry (FAT) is currently involved in the identification of requirements to allow a coupling of metal forming and crash simulation [11, 12].

Basic Approach for Carline Application

A more practical approach which can be implemented in a shorter time frame is the transfer of sheet metal thickness and equivalent plastic strain after the stamping process to the crash model. Important in this case is that the interface between a stamping analysis code (e.g. AUTOFORM) and the crash simulation code (e.g. RADIOSS) considers the requirement that the data of selected components as well as the whole model can be transferred. The assembly process needs to be reflected in the future development of commercial pre-processing tools.

To study the available opportunities of the current analysis codes used in production and to check the upcoming interfaces a model with a manual transfer of the scalar values ‘thickness’ and ‘work hardening’ is useful. Fig. 8 shows the deep-drawing and trimming process of the side rail out of a DP600 panel. Stamping tools of the Ford Focus front side rail were used to simulate this part.

As a result the strain-, thickness- and stressdistribution was obtained and transferred to the crash model of the crashtube, Fig. 9.

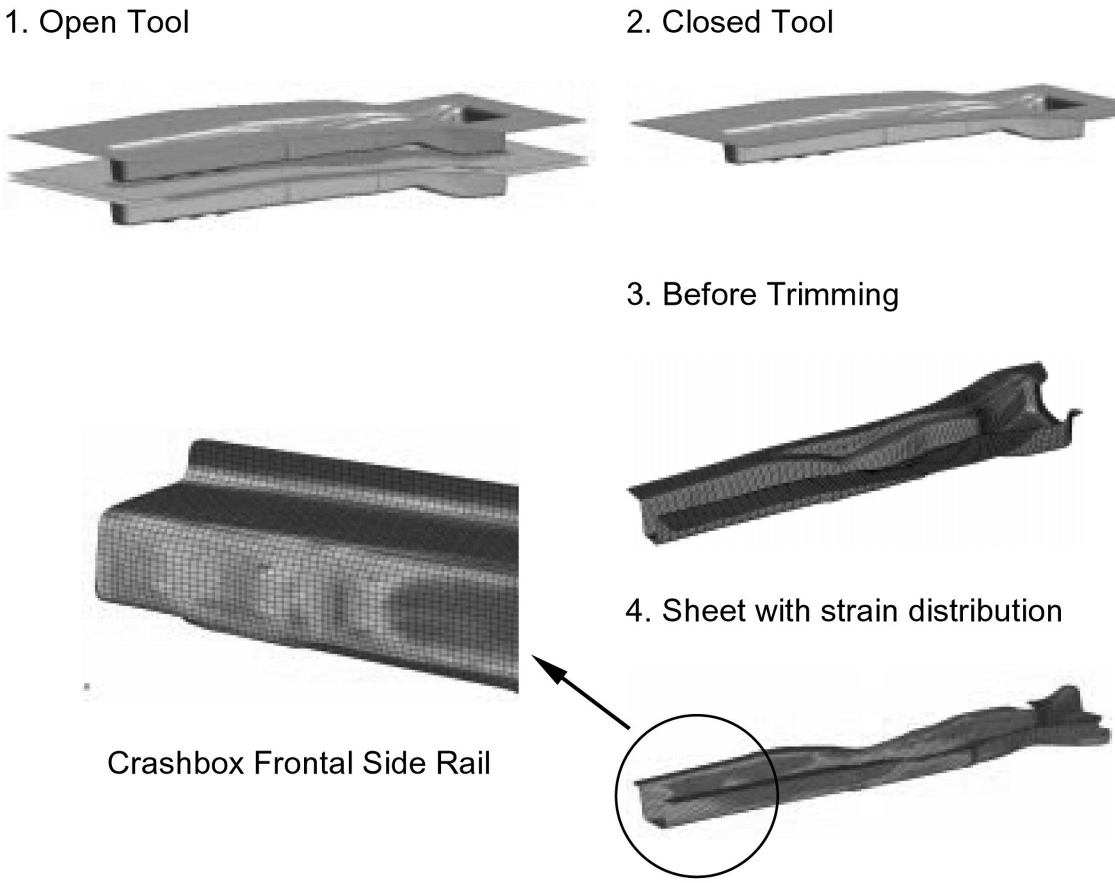


Fig. 8: Forming process of the frontal side rail

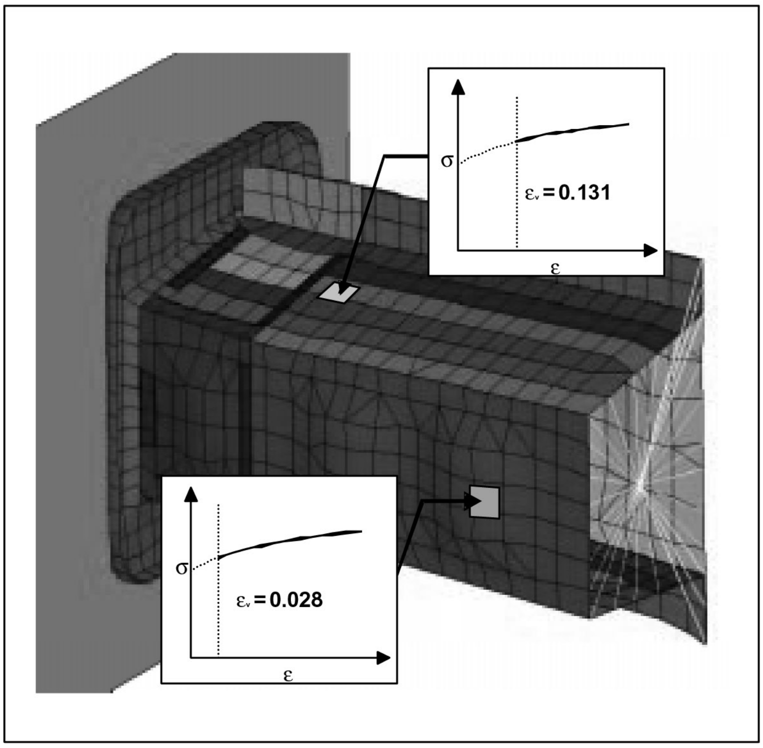
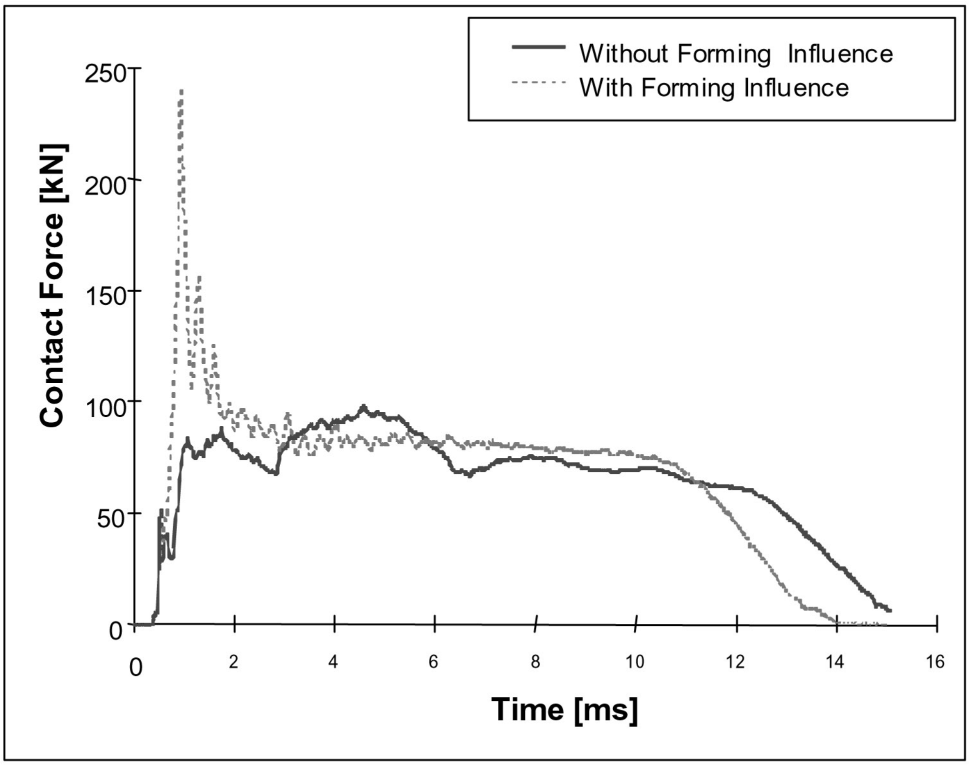


Fig. 9: Model of front rail considering the effects due to the stamping process

The side rail is crashed against a rigid wall with an energy which is defined by the initial velocity of 15 km/h and the mass of 200 kg added to the rigid body, Fig. 9. Fig. 10 identifies the influence of the stamping effect on the crash behaviour of this body part. The peak force is significantly higher and could result in plastic deformation in the rear area of the front end which would increase repair costs in low speed accidents. The mean force value is slightly higher (+5 %) which increases the energy absorption of this part. Full vehicle CAE models including this DP600 side rail component model are in preparation. Further studies - FE simulations as well as component tests - are ongoing to determine the influence of the manufacturing processes on the crash behaviour of the vehicle.



DP600 t_0 = 1.66 mm V_0 = 15 km/h

Fig. 10: Unfiltered force-time curve with and without stamping influence

Conclusion

Although the current explicit codes offer a wide range of material models, the application of advanced/new materials for passive safety requires a permanent improvement of these models reflecting, for example, the objective integration of constitutive equations, elastic-plastic damage modeling, strain rate dependent material parameters, coupling of metal forming and crash simulations. New models can be implemented by user subroutines based on the special requirements of passive safety applications. A co-operation with the software suppliers as well as with the material experts, e.g. steel or aluminium foam suppliers, is necessary to improve these material models in a consequent way.

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