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Steel processing effects on crash performance of vehicle safety related applications

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Abstract. Due to the increasing competition, automotive manufacturers have to manufacture highly safe and light vehicles. The parts which make up the body of the vehicle and absorb the energy in case of a crash, are usually manufactured with sheet metal forming methods such as deep drawing, bending, trimming and spinning. The part may get thinner, thicker, folded, teared, wrinkled and spring back based on the manufacturing conditions during manufacturing and the type of application methods. Transferring these effects which originate from the forming process to the crash simulations that are performed for vehicle safety simulations, makes accurate and reliable results possible. As a part of this study, firstly, the one-step and incremental sheet metal forming analysis (deep drawing + trimming + spring back) of vehicle front bumper beam and crash boxes were conducted. Then, crash performances for cases with and without the effects of sheet metal forming were assessed in the crash analysis of vehicle front bumper beam and crash box. It was detected that the parts absorbed 12.89% more energy in total in cases where the effect of the forming process was included. It was revealed that forming history has a significant effect on the crash performance of the vehicle parts.

Keywords: steel processing; vehicle safety; crash analysis; forming history

1. Introduction

Automotive manufacturers conduct many R&D studies to prevent the increasing number of traffic accidents or to mitigate their impacts. Accidents involving vehicles in traffic are frontal crash, rear crash, rolling over, side crash, 40% offset crash. The most common of these is 40% offset crash with 48.1%. The manufacturers are working on designs that would transmit the least damage to the driver and the passengers in case of an accident, considering these different types of accidents. Today, engineering designs and analysis are first performed on a computer, which saves time and money. The accuracy of the numerical analysis performed on computers constantly increase with the realistic acceptance and increasing number of input. In the crash simulations conducted with regards to the vehicle's crash safety, forming history of the parts manufactured with sheet forming methods on the vehicle are not transferred to the crash analysis and simulations are performed without taking these effects into consideration.

There are two important safety systems in safer vehicle designs. They are; the active safety systems (ABS, ESP, ASR) which aim to prevent accidents and the passive safety systems (Safety belt and air bags, front and rear bumper beams and crash boxes) which are triggered in cases where an accident is inevitable (URL 2016b, c). Bumper beams and crash boxes, which are passive safety systems, are systems that are used to prevent or decrease the damages to be caused by possible accidents in terms of materials and human health. Designing these parts considering the effects of forming will not only provide us with more reliable designs but will also contribute to vehicle light weighting works.

The literature shows a number of numerical and experimental studies on crashworthiness and sheet metal forming process. Zhang and Zhang (2016) studied crashworthiness performance of conical tubes with nonlinear thickness distribution. It was concluded that energy absorption and peak force of tubes change significantly after shrinking process. Schwindt *et al*. (2015) evaluated the forming limit curve of a DP 780 steel sheet. The standard test dimensions reduces by 60% with Nakajima tool geometry. Veillé *et al*. (2015) studied forming of thin-walled steel tube by means of an innovative incremental forming process close to spinning. Kiliclar *et al*. (2016) and Pipard *et al*. (2013) studied high-speed forming method and high strain rate experiments. Tamasco *et al*. (2012) and Najafi *et al*. (2012) suggested in their study that a coupled finite element simulation and optimization framework can be used for design and analysis of sheet-forming processes. Crashworthiness of thin-walled structures were presented by many authors. These researchs focus on different shaped structures, high strenght steels, sandwich and foam structures, effects of pre-strain and bake-hardening on the crash properties (Sun *et al*. 2014, Abedrabbo *et al*. 2009, Beik *et al*. 2016, Durrenberger *et al*. 2011, Azad and Saeed 2016, Zonghong *et al*. 2014). Springback and thinning compensation is another important

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topics in steel processing and crashworthiness. There is a large number of research which accurate springback prediction in deep drawing. Many authors proposed new methods for measuring and evaluating springback in sheet metal forming process (Hassan *et al*. 2016, Cafuta *et al*. 2012, Xue *et al*. 2016, Zhang *et al*. 2016).

A review of the existing studies in the literature revealed that the sheet forming analysis had usually been performed in one-step and that application parts had a simple geometry. In this article study both one-step and incremental analysis of sheet forming were conducted and their differences were identified. Additionally, bumper beam and crash boxes were chosen as vehicle front body energy absorptwion components for the automotive industry, as a part of application. Transferring the results of the incrementally performed sheet forming analysis to crash analysis revealed a significant difference in the absorbed energy and reaction force. Another striking point for this study is that, lots of papers in the literature assumed that selected vehicle parts are manufactured with a single forming stage, deep drawing process. But in the real, vehicle parts are manufactured after serious of forming stages as trimming and spring back. In this study, the effect of sheet metal forming history after serious of forming stages (deep drawing+ trimming+ spring back) as in the real was investigated.

2. Bumper beams and crash boxes

The bumper beam is the sheet metal part which is located inside the vehicle's exterior plastic bumper part and is used to mitigate the effect of the crash in case of an accident. Crash boxes are structures which are mounted on the metal bumper beam, usually by welding, and partially or wholly convert the kinetic energy released during the crash, into another form of energy. When a bumper beam and/or a crash box is to be designed, the goal is to absorb the majority of the crash energy internally and irreversibly. Therefore, human injuries can be minimized. Body structure and energy absorption components of a vehicle as shown in Fig. 1.

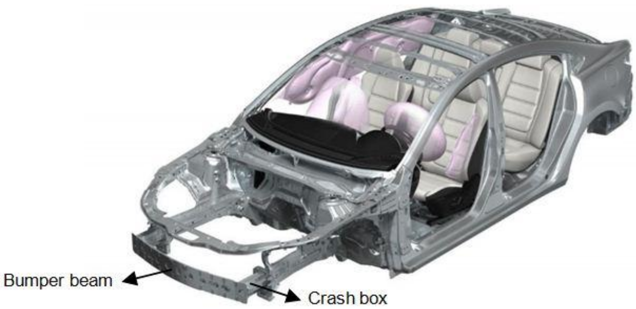

Fig. 1 Body structure and energy absorption components of a vehicle (URL 2016a)

The crash boxes which can be deformed; can be manufactured in the form of thin walled tubes (circular and square or prismatic), polygonal columns, tube shaped rings, comb like structures, sandwich planes and isolators. Additionally, these can be filled with foam to increase their energy absorption (URL 2016b). Sheet metal bumper beams which can be deformed; can be manufactured with roll form method, aluminium extrusion method, metal die method and hydroforming method. Criteria such as energy absorption, weight, manufacturability, cost, formability conforming to certain standards must be considered when designing bumper beam and crash boxes. Martensitic steel which has advanced formability, corrosion resistance and welding capabilities, dual phase steel which is 15% cheaper and has 20% more deflection resistance than the traditional high strength steel and aluminium materials are used when manufacturing bumper beam and crash boxes (Billur *et al*. 2016).

In the literature, several performance magnitudes were described in order to evaluate energy absorption capacity of vehicle parts. Performance magnitude is generally used to pre-design stage of vehicle parts. Total energy absorption can be described as Eq. (1) (Chathbai *et al*. 2007)

$$E_{absorbed} = \int P . d\delta \tag{1}$$

Where, P is the crushing force in the axial direction and δ is the displacement in the axial direction. This quantity is represented as the area under the axial force versus axial displacement curve. Secondly, the other performance magnitudes peak crash force, $P_{\max}$, is the maximum load experienced by the structure in the axial direction. The mean crush force, P_m, is defined by dividing the absorbed energy by the total crushing displacement, in the axial direction as presented in Eq. (2) (Jin and Altenhof 2007, Güler *et al*. 2010)

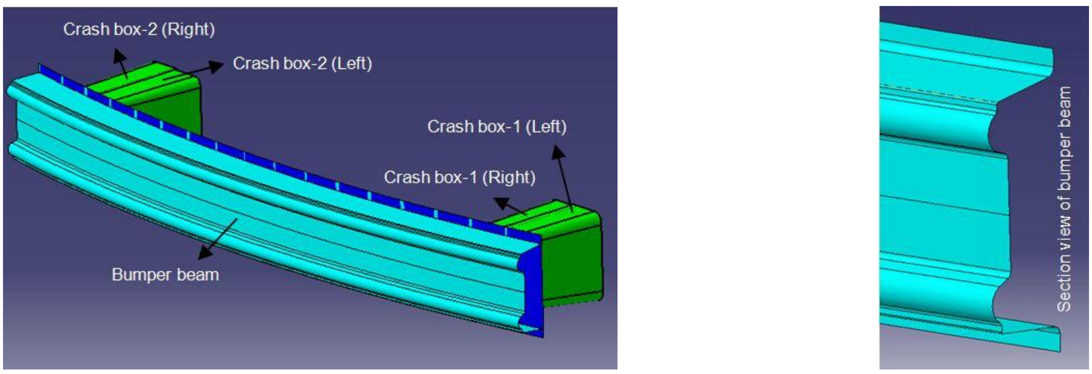

Fig. 2 Bumper beam and crash box modeling

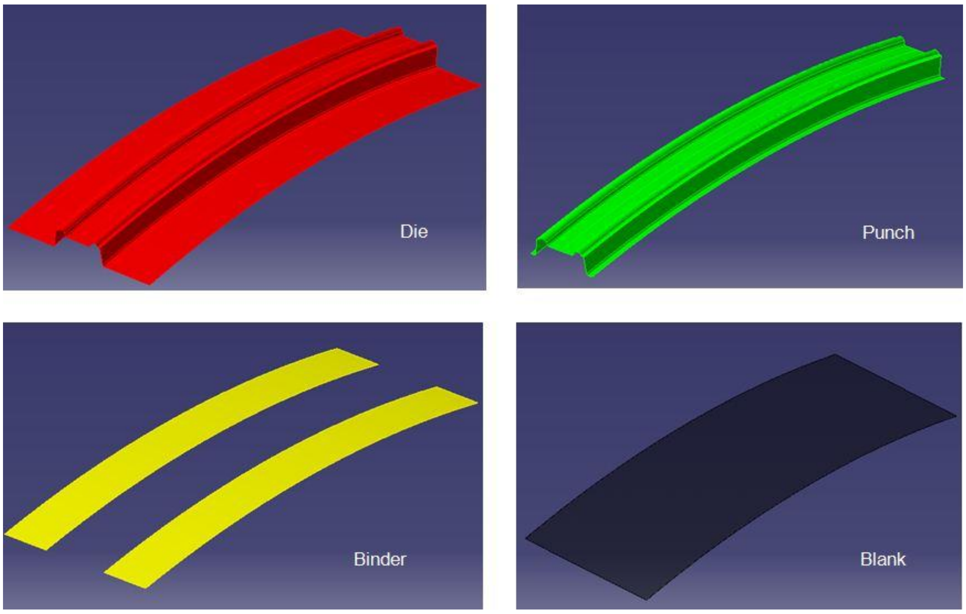

Fig. 3 The die geometry formed for the bumper beam

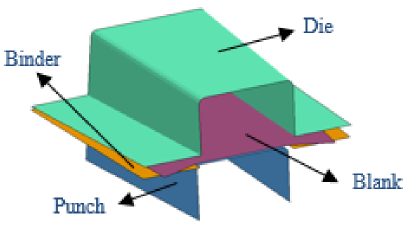

Fig. 4 The die geometry formed for the crash box

$$P_m = \frac{E_{absorbed}}{\delta_t} \quad (2)$$

The specific energy absorption (SEA) of a structure is the energy absorbed by a structure divided by its mass as defined in Eq. (3).

$$SEA = \frac{E_{absorbed}}{m} \quad (3)$$

where m is the mass of the absorber. This is a useful parameter that provides a method for comparing energy-absorbing structures with different masses (Güler *et al*. 2010).

3. Sheet metal forming analysis

3.1 CAD data of the bumper beam and crash boxes

Vehicle front bumper beam and crash box were modeled in CATIA surface module as seen in Fig. 2. Right and left crash boxes are modeled as two pieces. Wall thickness of bumpers and crash boxes is 1.5 mm.

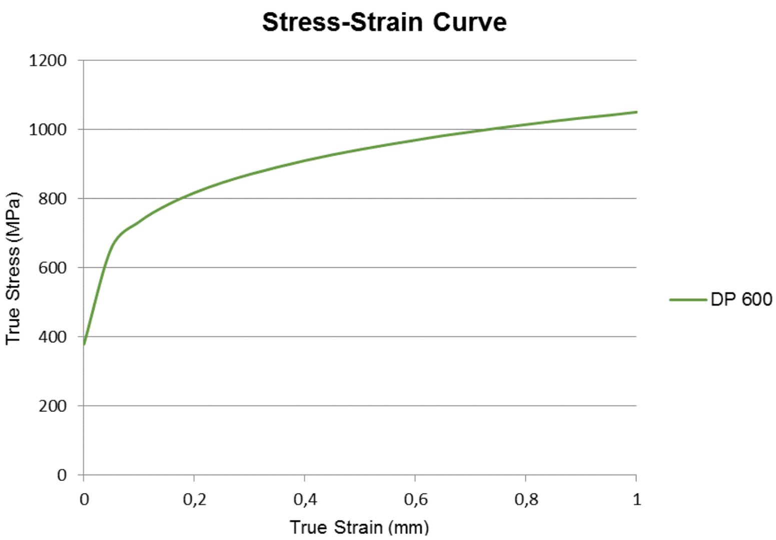

Fig. 5 Stress-Strain curve of DP 600

Fig. 6 Deep drawing analysis performed for the bumper beam and the crash box

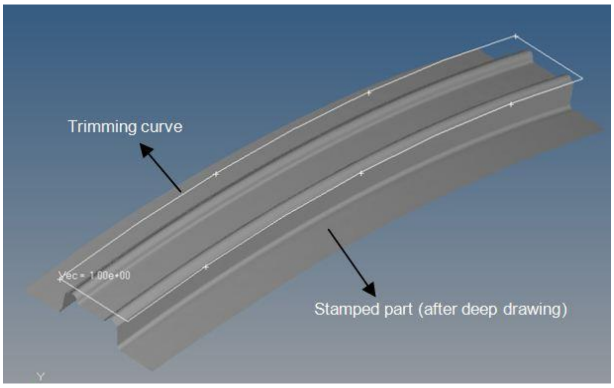

Fig. 7 Trimming analysis performed for stamped bumper beam

3.2 Creation of die geometry for bumper beam and crash boxes

As seen in Figs. 3 and 4, die geometry is formed for bumper beam and crash box. Die geometry is composed of die, punch, holder and blank.

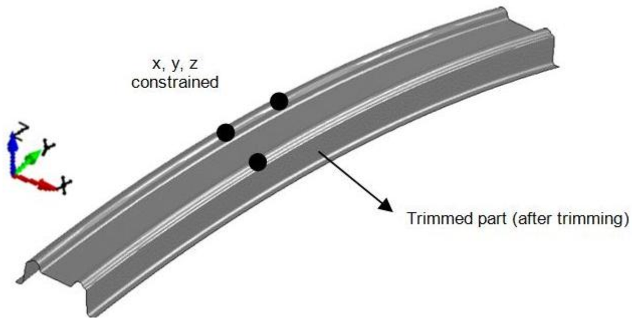

Fig. 8 Springback analysis performed for trimmed bumper beam

Table 1 The mechanical characteristics of DP 600 steel

E(GPa)	$\sigma_y(MPa)$	v	K(MPa)	R_0	R_{45}	R_{90}	n	ε_0
210	379	0.3	1076	0.97	1.07	1.17	0.189	0.0026

3.3 Finite element model and material

The finite element model of bumper beam and crash box die geometry was performed on LS-PrePost software. The bumper beam and crash boxes used in this study were made out of DP 600 steel. Barlat Material model (MAT 36) was used as the material model. The mechanical characteristics of the DP 600 steel that was used can be seen in Table 1. Also stress-strain curve of DP 600 can be seen in Fig. 5.

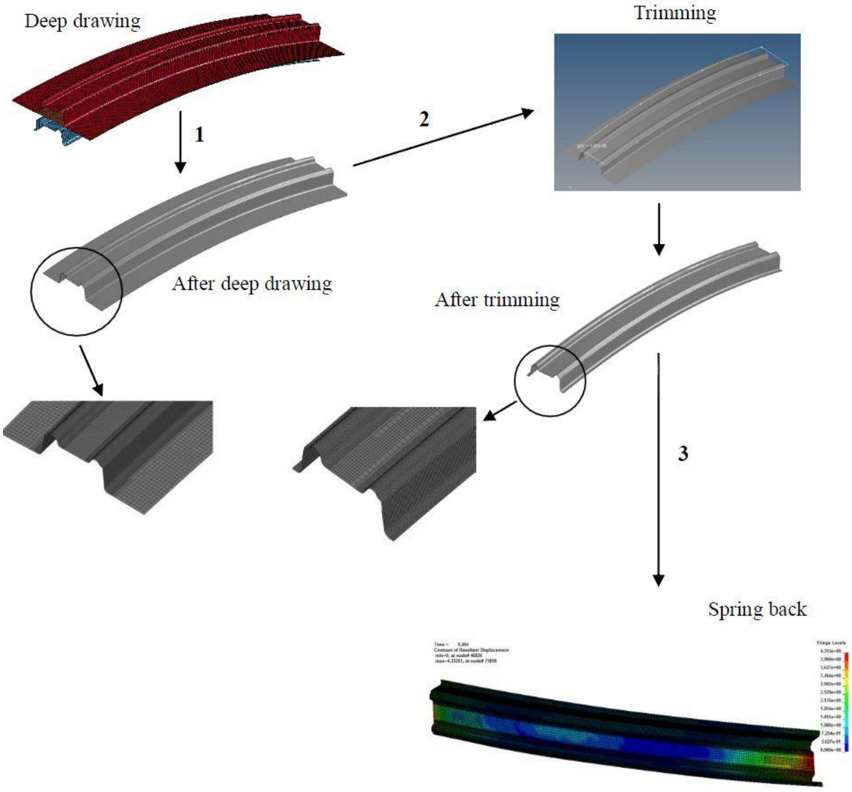

Fig. 9 Deep drawing, trimming and spring back analyses of bumper beam

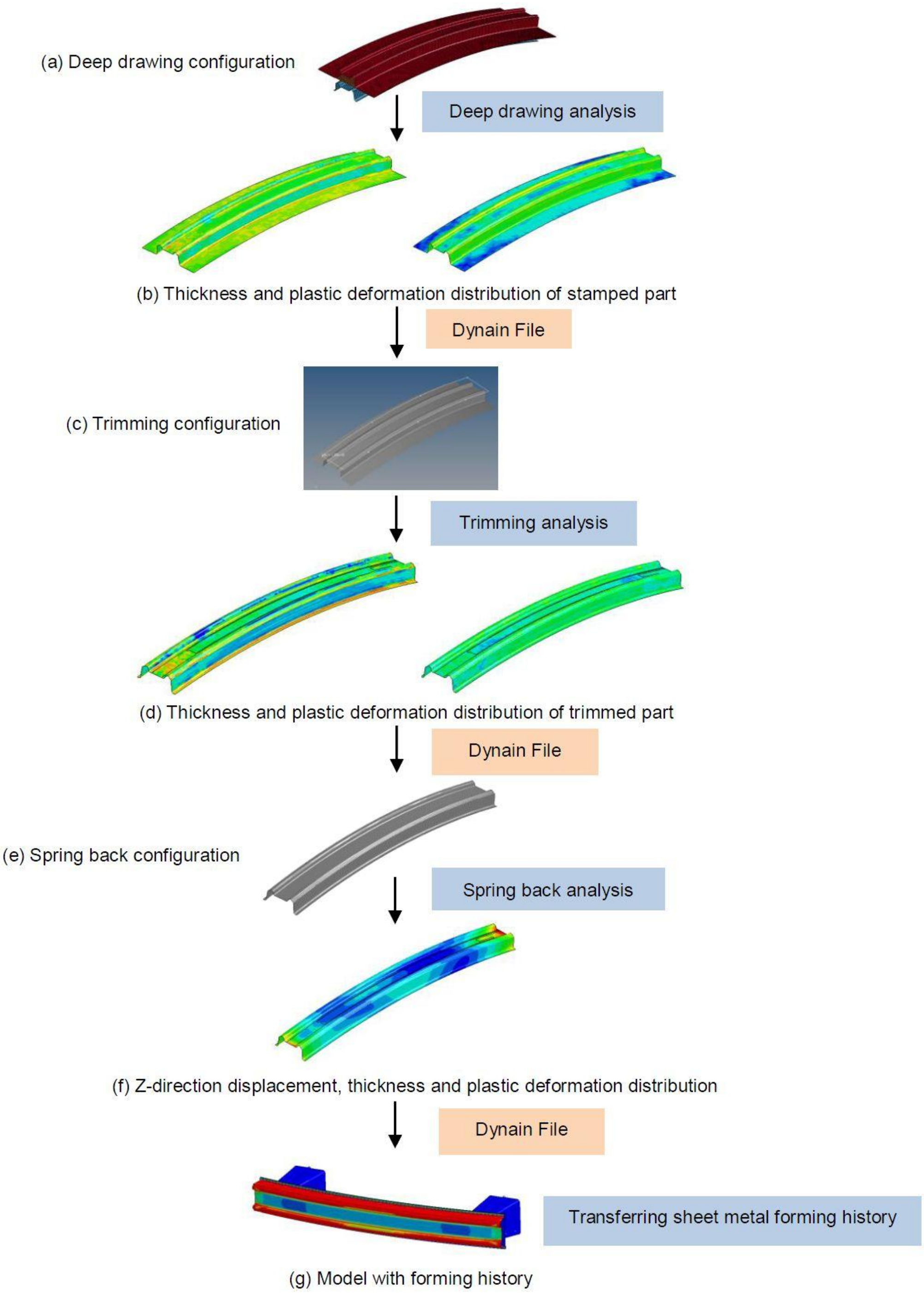

Fig. 10 Transferring the forming history to the crash analysis

Table 2 The thickness change in the parts after sheet forming analysis

Part	Initial thickness (mm)	Minimum thickness (mm)	Maximum thickness (mm)
Bumper beam	1.5	1.221	1,511
C. Box-1 (Right)	1.5	1.109	1.542
C. Box-1 (Left)	1.5	1.2	1.531
C. Box-2 (Right)	1.5	1.129	1.526
C. Box-2 (Left)	1.5	1.095	1,538

In Table 1, E represents the elasticity module, σ_y, represents the yield stress, v, represents the poisson's ratio, K, represents the strain-hardening coefficient, R_0, R_{45}, R_{90} represents the three way anisotropy value and n represents the strain-hardening exponent.

3.4 Boundary conditions

Belytschko-Tsay model was used as element formula-ion in the deep drawing analysis conducted for bumper beam and crash box shown in Fig. 6. Deep drawing direction is the Y axis. "Forming one way surface to surface” was chosen as type of contact. The moving part in the die geometry is the die and the closing speed was chosen as 1 m/s and the opening speed was chosen as 5 m/s. Belytschko-Tsay element formulation was used in the trimming analysis conducted for bumper beam shown in Fig. 7. It was chosen fully integrated shell and number of integration (NIP) is 5. Gravity direction is the Z axis. Trim outline line (curve) was chosen as shown in Fig. 7. Minimum element size is 0.25, maximum trimming gap is 20. For spring back simulations; element formulation, shell type, NIP was same with trimming. Gravity direction is the Z axis. It was picked tree nodes in the X, Y, Z axis as constraint shown in Fig. 8.

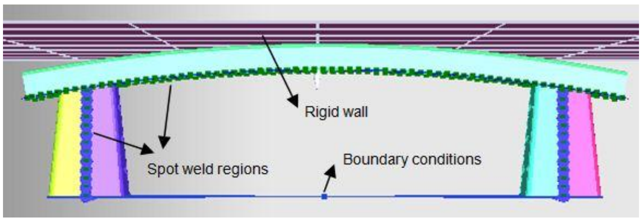

Fig. 11 Descriptions regarding the crash analysis

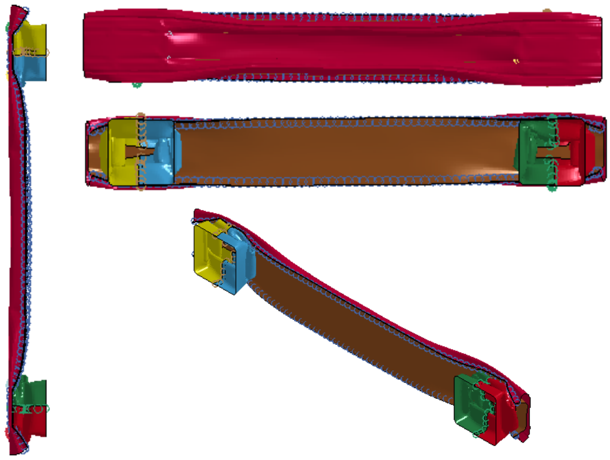

Fig. 12 Results of crash analysis with different angles

3.5 Results of analysis

A total of 5 deep drawing analyses were conducted for one bumper beam and two crash boxes (two parts, left and right) for this study. Also total of 1 trimming (for bumper beam) and 5 spring back analyses were conducted for one bumper beam and two crash boxes (two parts, left and right). All of these analyses for bumper beam can be seen in Fig. 9. Effects such as thinning, thickening, plastic deformation, folding, tearing, wrinkling and spring back can be seen in the parts leaving the die after the forming process. These effects vary depending on the die geometry, die material and type of forming. Table 2 shows the thickness changes in the parts after the forming process.

4. Crash analysis

4.1 Transfer forming history to crash analysis

Effects such as thinning, thickening, plastic deformation, folding, tearing and wrinkling seen in the part after the forming analysis of bumper beam and crash boxes, are transferred to crash analysis. The steps of this transferring process can be seen in Fig. 10. Parts undergoing sheet forming process have a certain thickness distribution and plastic form change distribution after they leave forming process. These values can be transferred to the crash analysis with the “dynain” file in Ls-PrePost software.

4.2 Definitions for crash analysis

The finite elements model and material (MAT 36) definitions of the bumper beam and crash boxes were created with Altair HyperMesh software. As seen in Fig. 11, the crash boxes, which are in separate parts, are bonded with one another and the bumper beam with spot welding. The passive safety system compromising of the bumper wall at 4.44 m/sec (16 km/h). “Automatic single surface” was used in the contact definition between the rigid wall

Table 3 The parts’ energy absorption capacities by comparison [kJ]

	One-step analysis			Incremental analysis		
Part	Sheet forming effect not included	Sheet forming effect included	% Difference	Sheet forming effect not included	Sheet forming effect included	% Difference
Bumper beam	0.484	0.507	4.752	0.484	0.569	17.56
Crash boxes	5.661	5.717	0.989	5.661	6.368	12.48
Total	6.145	6.224	1.285	6.145	6.937	12.89

Table 4 Reaction force of the parts by comparison (peak force) [kN] (109 mm for displacement)

	One-step analysis			Incremental analysis		
Part	Sheet forming effect not included	Sheet forming effect included	% Difference	Sheet forming effect not included	Sheet forming effect included	% Difference
Total (Bumper beam + crash boxes)	224.1	242.6	8.255	224.1	256.5	14.45

beam and crash boxes was made to crash into a 1650 kg and the passive safety system.

4.3 Results of analysis

Crash analyses were performed for two cases. The first is the crash analysis where the effect of forming was not considered while the other is the analysis where the effect of forming was considered. The forming analysis of the bumper beam and crash boxes was performed in two ways as well. The forming effects of the part formed without creating a die geometry can be seen in the first one, which is one-step analysis. In incremental analysis; however, die geometry is created in detail, all forming parameters are defined and a more realistic forming analysis is performed. Tables 3 and 4 show the absorbed energy and maximum reaction force values for cases where forming effects are and are not included. Fig. 12 show results of crash analysis deformation with different angles.

5. Conclusions

The mathematical model and the software are constantly improved to achieve more realistic results in computer-aided design and analysis. The dynamic characteristics of the material as well as the effects of the changes originating during the forming process must be considered in order to make the crash simulations performed for the automotive industry more realistic. Parts making up a significant portion of the body of the vehicles are manufactured with sheet forming methods. Non-uniform distribution of thickness and plastic deformation and thinning and folding due to forming may occur in the parts depending on the manufacturing conditions during manufacturing and the method. Most of the studies have been conducted without considering the effects of the forming process. Not considering these effects cause false results in crash simulations. Effects of the forming process on crash performance in front bumper beam and crash boxes used in the vehicles were studied and the following results were obtained:

- It was revealed that forming history has a significant effect on the crash performance of vehicle the parts.
- When the energy absorption amounts of the bumper beam and crash boxes were singularly examined in accidents with frontal crashes, it was seen that the crash boxes absorbed much more energy than the bumper beam. In other words, crash box is the part that absorbs the most energy in a frontal crash.
- Results obtained by transferring the effects of sheet forming from incremental analysis to crash analysis are more realistic than the results obtained by transferring the effects of sheet forming from one-step analysis to crash analysis.
- By transferring the forming history to the crash analysis, energy absorption capacity of the bumper beam part increased by 4.752% in one-step analysis and 17.56% in incremental analysis.
- By transferring the forming history to the crash analysis, energy absorption capacity of the crash boxes increased by 0.989% in one-step analysis and 12.48% in incremental analysis.
- By transferring the forming history to the crash analysis, the peak value of the reaction force increased by 8.255% in one-step analysis and 14.45% in incremental analysis.
- By transferring the forming history to the crash analysis, the total energy absorption capacity of the parts increased by 1.285% in one-step analysis and 12.89% in incremental analysis.
- The bumper beam and the crash boxes are the parts that are tasked with minimizing the effect of the accident to the driver and the passengers in case of an accident with frontal crash. Therefore, the correct design and analysis of these parts are vital.
- Deep drawing process effects like thinning, thickening, folding, tearing, wrinkling have a significant impact on crash simulation result compared to trimming and spring back effects. Because thickness distribution is changing during deep drawing process and plastic deformation amount of deep drawing process is higher than other sheet metal forming process.

It was detected that the parts absorbed 12.89% more energy in total in cases where the effect of the forming process was included. If the forming history had not been transferred to the crash analysis, the total energy absorbed by the parts would have been detected to be 12.89% less. With the study, it is possible to design bumper beams and crash boxes to provide more than the required amount of energy absorption. In other words, the cross section area and wall thickness of bumper beams and crash boxes may be decreased with the feedback from these results of analysis. This could have significant effect on decreasing the vehicle weight in the automotive industry where vehicle light weighting works increase.

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