CAE analysis and simulations of technological processes of selected high strength steels

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Abstract. The article of authors deals with the design of the structural part of the bodywork in the CAE system CATIA using the CAE software solutions of the Autoform system, which are based on the finite element method. This design was subsequently implemented into the design of dies in order to achieve the most efficient and high-quality dies, which are increasingly required in industrial practice for lifetime and functionality. Three types of high-strength steels TRIP HCT780T, DP-HCT780X and CP-HCT780C with approximately the same tensile strength were selected for the experiments. Based on the input parameters, simulations were implemented and the results obtained from the simulations will be the basis for selecting the most optimal variant. The main measurable and evaluative factor was the outputs obtained from the FLD diagrams.

1. Introduction

In recent years, the role and importance of metal forming processes in the manufacturing industry has steadily increased, mainly due to their material and cost-effectiveness. Great emphasis is placed on recent advances in tools, materials and design, which in turn bring significant improvements in mechanical properties and product tolerances. In addition, in recent years, metal forming has been developed in the direction of production in the form of a cross-linked model or a close cross-linked model, in order to reduce the need for subsequent machining operations and to minimize overall manufacturing costs.

The application of various CAE techniques practically covers the entire product development cycle from conceptual product design through process planning to the production phase. CAE techniques are widely used in sheet metal forming, for example in predictability of formability, in determining the type and sequence of production processes and their parameters, in the design of forming tools, etc. As the need for widespread application of CAE techniques driven by global competitiveness demands is accelerating, the need for robust and simplified process and design engineering is becoming increasingly important.

Abspoel et al. [1] reported a new method for predicting forming limit curves from mechanical properties of investigating steels which included cold-rolled and hot-rolled forming steels, dual-phase DP steels, TRIP steels and much more. Tang et al. [2] brought an improved damage evolution model to predict fracture of steel-sheet at elevated temperature. Frómeta et al. [3] performed different mechanical tests in order to characterize the fracture resistance of the studied steel sheets and rationalize the cold forming behaviour. Also sheet metal formability evaluation performed in their research authors Cui et al. [4], Bandyopadhyay et al. [5], Kim et al [6] and also Holmberg et al. [7].
Calibration of forming limit diagrams using a modified Marciniak-Kuczynski model and an empirical law were performed by the authors Ghazanfari and Assempour [8]. Experimental investigation studies of forming limit diagram and the simulation of sheet metal forming processes were performed by the authors Korhonen and Manninen [9], Banabic and Vos [10] and collective of authors Jie et al. [11]. Application of modern technologies, progressive methods of heat treatment and high-strength steel steels in special engineering application presented in their papers some collectives of authors Dubovská and Majerík [12], Pokorný et al. [13] and Sedlák et al. [14].

There are currently two main approaches to achieving these objectives. One of them is application of knowledge expert systems, which are usually based on simplified theory of plasticity and empirical technological rules. However, only knowledge-based solutions have certain disadvantages: they usually cannot provide a sufficiently accurate solution to the problem, as these systems are generally based on simple technology rules of limited validity. Knowledge-based systems, therefore, cannot predict material flow, for example, and usually cannot provide accurate stresses and internal component layouts.

Despite the huge development of hardware and software devices, the reliability of results is often dependent on the user's experience. This is partly due to the large number of input parameters whose impact should be investigated and partly due to numerical difficulties due to the complexity of the mathematical model used to describe the behaviour of the material. Therefore, the integration of these two areas has become of primary importance in recent years. systems based on knowledge and numerical modelling.

As a further approach, numerical techniques (most recently finite element modelling) are used to analyse plastic deformation. The main objectives of numerical simulation of metal forming processes are to identify appropriate process parameters and develop adequate tool design by process simulation, improve part quality by predicting process limits, and avoiding drag-induced defects. In addition, the simulation of numerical processes also leads to a reduction in the design time of the die tool design, tests as well as shortened delivery times, significantly reducing production costs.

2. Materials and methods
The main task of realized experiments is to process and analyse deep-load simulations in order to achieve optimal process of forming of reference moulding. At the beginning we will describe the design and function of the reference part of the car body. On the basis of the reference part we will process a pressing method containing all necessary operations necessary for pressing the reference part. Based on the pressing method, we design the drawing tool. In the experimental part will be investigated and set respectively the optimal process pressing technology using simulation software Autoform. Given the increasingly stringent conditions of the automotive market for weight reduction, increased safety and the cost of cars, we will investigate and fine-tune the process on three types of progressive high-strength steels to determine the right material for the reference part. In the drawing process we will work with the geometry and micro-geometry of the active parts of the tool, whose optimum values will be evaluated in the final processing of the simulations of individual materials.

2.1. Experimental materials
Three types of materials were chosen for realization of the experiments: TRIP steel - HCT780T, DP steel - HCT780X and CP steel - HCT780C.

The microstructure of TRIP steels is stored by austenite anchored in the primary ferrite matrix. In addition to at least five percent by volume of the retained austenite, hard phases such as martensite and bainite are present in different amounts. TRIP steels usually require the use of medium temperature isothermal heat that produces bainite. The higher silicon and carbon content of TRIP steels results in significant austenite volume fractions in the final microstructure. Upon deformation, the hard second phases disperse in the soft ferrites, resulting in high working curing, as observed in DP steel. In TRIP steels, however, the retained austenite gradually changes to martensite with increasing stress, thereby increasing the cure rate at higher stress levels.
Dual-phase DP steels consist of a ferritic matrix containing a hard martensitic second phase in the form of so-called islands. Increasing the bulk fraction of solid second phases generally increases their strength. DP (ferrite and martensite) steels are produced by controlled cooling from the austenite phase (in finished rolled products) or from the two-phase ferritic and austenite phases (for continuously annealed cold and hot dipped products) austenite to ferrite transforms the remaining austenite martensite. The microstructure of DP steel contains ferrite and islets of martensite. The soft ferrite phase is generally continuous, giving these steels an excellent ductility. When these steels are deformed, the strength concentrates into a lower strength ferrite phase that surrounds the martensite islands, creating the unique high initial working hardness (n-value) these steels show.

CP steels represent the transition to steel with a very high tensile strength. The microstructure of CP steels contains a small amount of martensite, retained austenite and perlite in the ferrite / bainite matrix. Extensive grain refinement is due to delayed recrystallization or precipitation of microalloyed elements such as Ti or Nb. Compared to DP steels, CP steels exhibit a significantly higher strength at the same tensile strength of 800 MPa and higher. CP steels are characterized by high energy absorption, high residual deformability and good expansion.

Due to the strength properties of the reference part, steels with the same breaking strength of 780MPa were used. The simulation will use a constant sheet thickness of 1mm. The main difference in materials is their ductility, which is one of the decisive factors in forming. The tables below compare the mechanical properties (table 1) as well as the chemical composition (table 2) of the materials used in the simulations. In terms of chemical composition of materials, they are similar except for the increased Si value and the reduced Cr and Mo values in TRIP steel. In terms of mechanical properties, the most important difference is the value of the overall elongation of the individual steels.

**Table 1. Comparison of mechanical properties of simulated steels.**

| Steel     | Tensile strength $R_m$ (MPa) | Proof stress 0.2 $R_{p0.2}$ (MPa) | Elongation $A_5$ (%) |
|-----------|------------------------------|-----------------------------------|---------------------|
| HCT780T   | 830                          | 450–570                           | 24                  |
| HCT780X   | 780                          | 440–550                           | 14                  |
| HCT780C   | 780                          | 570–720                           | 10                  |

**Table 2. Comparison of chemical composition of simulated steels (wt. %).**

| Steel     | C   | Si  | Mn  | P   | S   | Al  | Cr+Mo | Ti+Nb | V   | B    |
|-----------|-----|-----|-----|-----|-----|-----|-------|-------|-----|------|
| HCT780T   | 0.25| 2.20| 2.50| 0.08| 0.015| 0.015–2.0 | 0.60  | 0.20 | 0.20 | 0.005|
| HCT780X   | 0.18| 0.80| 2.50| 0.08| 0.015| 0.015–2.0 | 1.40  | 0.15 | 0.20 | 0.005|
| HCT780C   | 0.18| 1.00| 2.50| 0.08| 0.015| 0.015–2.0 | 1.00  | 0.15 | 0.20 | 0.005|

**2.2. Methods of simulation**

In the first step, the optional parameters of the first steel TRIP - HCT780T were set. In the simulation process, manual setting of optional simulation parameters was selected. The same procedure with the same parameters was chosen for the other materials DP - HCT780X and CP - HCT780C. The selected and set parameters for the initial simulation were brake ribs – brake factor, shape of brake ribs, pressing force, clamp force, cut size. Subsequently, the parameters of the material folding type, the risk of ripple, the risk of cracking, the safe area for optimal yield of the simulation based on the FLD diagram i.e. diagram of limit deformations.
In the process of drawing process simulation, it is possible to work with a number of input parameters and it is also possible to change them in different order or to bypass them completely. For this reason, individual optimization steps were carried out in the absence of zero simulation results.

Optimization step number 1, i.e. adjustment of the optional input parameters (brake ribs position 1, 2, 3, 4, shape of the brake ribs, pressing force, holding force, cut size). Any positive change in the optional input parameters can significantly improve the safe area in the FLD diagram.

Optimization step number 2 is used if it is not possible to achieve the optimal state of the tensile simulation when changing the optional input parameters, it is necessary to change the geometry of the tensile surface. The work is based on the most successful simulation from optimization step 1 and the tensile surface on the centre of gravity and matrix is adjusted at critical points. The best option is to change the so-called towing radii.

Optimization step 3 is used in the simulation process if it is not possible to achieve the optimum state of the stroke simulation when changing the optional input parameters and the stroke area does not proceed to the design of the reference part changes. These changes must take into account the concept of the car body and we must not affect its functionality in all respects. For this reason, it is only proposed to loosen the radii locally in order to reduce the cracks, and possibly to add reinforcements to better switch off the yield.

The method of determining the results was solved by evaluating each simulation based on the FLD diagram of the forming of the reference part, where the limit deformation values are displayed on the part using a colour map, which is identical to the FLD values of the individual simulations. When comparing the individual maps of each simulation, you can see how the adjustments of the input optional parameters have effect.

The evaluation of realized simulations was in the process of realized experiments on the dimension of the reference part and not on the whole yield due to the fact that the rest of the sheet goes to recycling.

3. Results and discussion

3.1. Simulation of TRIP HCT780T steel

A graphical representation of the TRIP HCT780T steel simulation results can be seen in figure 1 and figure 2. The simulation shows all values correctly.

![Figure 1](image1.png)

**Figure 1.** Representation of FLD diagram results on a TRIP HCT/80T steel test piece.

The area of risk of cracking and cracks on the parts did not appear. In part, the area of under-stressing of the part at the edges of the moulding is reported, but the values are within the tolerance limits (figure 1 and figure 2).

In the zero simulation process of optimization, the following changes have been realized, such as snip size and brake 3.4.
After the all changes have been done, the final simulation shows all values correctly. The area of risk of cracking and cracks on the parts did not appear. The area of insufficient part turning off at the edges of the moulding has improved, and the values are within marginal tolerances.

Figure 2. Results of final simulation No.1 of TRIP HCT780T steel.

3.2. Simulation of DP HCT780X steel
A graphical representation of the DP HCT780X steel final simulation results can be seen in figure 3 and figure 4. The simulation shows unsatisfactory values. The area of risk of cracking and cracks on the parts appeared symmetrically in the inclined walls. In part, the area of under-stressing of the part at the edges of the moulding is reported, but the values are within the tolerance limits. For this reason, we have reduced the braking factor to eliminate cracking and hence reduce the area of cut-off. Based on the results obtained from the zero simulation, the following changes were made, such as the cut-off size, brake 1-seg2, 2-seg2, 3, 4.

Adjustments in simulation 1 showed positive results, but the simulation still shows unsatisfactory values. The area of risk of cracking and cracks on the parts has been reduced. The area of insufficient part turning off at the edges of the moulding has been partially deteriorated, but the values are within marginal tolerances. Given the positive results, we continued to reduce the braking factor in order to eliminate cracking again, and we anticipated a reduction in part shutdown. Based on the results obtained and the subsequent first simulation, changes were also made, such as brake 1-seg1 and 3, 2-seg1 and 3, 3, 4 and also a reduction in the gripper force.

After the changes have been made, the simulation 2 (see figure 3 and figure 4) shows all values in the standard. The area of risk of cracking and cracks on the workpiece has been reduced to a tolerance level. At the same time, the crimping value of the compact was halved. Insufficient turning off of the part at the edges of the moulding remained almost unchanged, and the values are within the margins of tolerance.

Thus, the simulation is correctly set for the DP HCT780X material and the simulated part is therefore within the compressibility tolerance. To achieve even better results, the possibility of simulating in the second step of the process diagram would be to change the shape of the tensile area in the cracking area i.e. opening radii. An additional assessment of the suspension, dilution and crimping of the compact on the finished simulation is standard.
3.3. Simulation of CP HCT780C steel

The initial simulation of CP HCT780C steel showed absolute unsatisfactory values. The area of risk of cracking and cracks on the parts appeared symmetrically in the inclined walls but also along the entire part. Value exceeds maximum 11 times. In part, the area of under-stressing of the part at the edges of the moulding is reported, but the values are within the tolerance limits. As part of the measures, we had to edit multiple parameters. Based on the results obtained from zero simulation, the following changes were made, such as the size of the cut, Brake 1-seg2, 2-seg2, 3, 4, as well as the reduction of the gripper force.

The simulation showed again unsatisfactory values after the first adjustments. The crack area was halved and the crack area was reduced to 2 times the value. Positively began to remove the longitudinal crack at the level of the whole part. Partially the area of insufficient part turning off at the edges of the moulding is reported, but the values are within marginal tolerances. The measures were successful therefore we continued to modify the same parameters. Based on the results obtained from the previous simulation, the following changes were made, such as brake 1-seg1 and 3, 2-seg1 and 3, 3, 4, as well as a reduction in the gripper force.
The simulation showed again unsatisfactory values after two previous adjustments. The area of risk of cracking was unchanged. The crack area was positively improved to a level just above the margin of tolerance. The adjustments had a negative impact on part offsets and ripple at extrusion edges that exceeded tolerance limits. Given the most important cracking parameter, we had to continue to optimize the parameters at the expense of part shutdown and ripple. Therefore, the following changes were made again: such as 1-seg2, 2-seg2 brake, as well as a reduction in the gripper force.

After subsequent changes, the final simulation (figures 5 and 6) showed the cracking values in the standard. The area of risk of cracking and cracks in the workpiece has been reduced to a tolerance level. Longitudinal cracks in the part were also removed by optimizing the parameters. As expected, the adjustments had a negative impact on the cut-off and ripple of the workpiece at the margins, which partially exceeded the tolerance limits. After careful analysis of the ripple height not exceeding 0.02 mm, we consider the last simulation to be usable.

The simulation is set to the tolerance limits for TRIP HCT780C steel. To achieve better results, it would be possible to simulate in the second step of the process diagram and to change the shape of the tensile area in the cracking area such as loosening the radii. As a more appropriate solution, it would be necessary to use the possibilities of the third step of the process diagram to propose a change of part. An additional assessment of the suspension, dilution and crimping of the compact on the finished simulation is standard.
4. Conclusions

After performing the so-called zero simulations, it was necessary to optimize each material to a greater or lesser extent. All changes made to the input optional parameters were recorded in the Autoform simulation software, and in the results of the final simulations can we see the effect of changing individual parameters on the forming process.

![Graph](image)

**Figure 7.** Comparison of selected mechanical properties of investigated TRIP, DP and CP steels.

TRIP HCT780T steel was characterized by excellent properties for forming the reference part. This is primarily due to the 24% elongation value, which has already achieved a satisfactory result in a zero simulation. During the optimization, we also managed to achieve a reduction of the cut size by 10mm per side, which is a positive for customers in terms of cost savings. Due to the good results we see the possibility of using TRIP steel with higher strength, which would increase the coefficient of safety of the car. Another alternative would be to use higher strength TRIP steels and reduce sheet thickness, thereby reducing the weight of the vehicle with similar safety characteristics.

DP HCT780X steel showed average forming properties of the reference part. The elongation value of 14%, with no simulation, was not sufficient. During the optimization, the desired result was achieved just below the limit values. It can be seen from the simulation that by reducing the braking factors and reducing the holding force, the ripple area increases. In complicated areas and corners of the workpiece, it has been found that the material is difficult to handle the deep pulling resulting from spherical radii. This implies the suitability of the material for both pulling and bending. The simulation was also successful based on the FLD diagram analysis.

CP HCT780C steel has unsuitable properties for forming the reference part. The elongation value of 10%, with no simulation, was not sufficient. Subsequent optimization succeeded in achieving a suitable result just below the cracking limit values, but the part was not sufficiently switched off and excessively undulating. By reducing the braking factors and reducing the holding force, the ripple area has increased significantly. In complicated areas of the corners of the work, it has been found that the material is difficult to handle the deep pulling resulting from spherical radii. This was also shown in simulations no. 0 to 2 on cracking along the entire part. This implies the suitability of the material for bending and not for drawing deep mouldings. Simulation with a reduced part thickness of 0.7 mm was tested for optimization, which represents a reduction of material by 30%. The simulation despite the
measure was unsuccessful in the cracking range. The output was also evaluated based on the FLD diagram analysis.

When comparing individual simulation results and their subsequent optimizations, it was concluded that the most suitable material for forming the reference part was TRIP steel due to its sufficient margin in comparison with the limit values.

DP steel was a good compromise for the reference part. It has achieved positive forming results even with low ductility and thus has the possibility to apply also to parts using bending technology. CP steel with its mechanical properties is more intended for bending technology, although after optimization, a positive simulation result was achieved, but at the expense of sufficient part shutdown.

In the case of continuation of the drawing technology, it would be necessary to intervene in the shape of the reference part. The overall graphical evaluation of the mechanical forming properties of the individual types of TRIP, DP and CP steels is evaluated in figure 7.

5. References
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