Finite Element Indentation Analysis of Automotive Roof Panel using Ultra Low Carbon Steel with and without Bake Hardening Effect

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Abstract. Ultra-low carbon (ULC) steels, which are lightweight, are used in fabricating steel sheets for many applications, particularly the automobile sector where good formability and surface quality are required. For mechanical properties development reasons, the bake hardening technique of ultra-low carbon (ULC) steels is adopted during the automotive paint baking process at elevated temperature. Automotive outer body with bake-hardenable steel ensure good indentation strength and resistance to fatigue. Usually, the mechanical properties of automotive steels depend both on the chemical composition and thermal treatment. Consequently, the present paper aimed to design a car roof panel using elastic-plastic ULC steel sheet with and without bake hardening. Finite element (FE) analysis was used to predict the static indentation response of automotive roof panels. First of all, the roof panel was modelled via CATIA V5 and evaluated by FE analysis using ABAQUS Software. The results showed that the bake-hardenable steel sheets present a good indentation strength and less plastic deformation.

1. Introduction

Nowadays, many manufacturers from automotive sector are involved in intensive research of lightweight vehicles, while respecting the safety requirements and the environmental regulations. Despite of competing materials such as aluminum and composites, the steel remains the automotive king material. The development of a new steel for an automotive component needs both a review of design and manufacturing process, whilst keeping the opposite qualities: strength and formability. The core problem for steel is that more it is strength, less it is formable, to combine these two qualities, two classes of steel they made a breakthrough, DP (Dual-phase), followed by TRIP (Transformation induced plasticity) whose mechanical properties obtained by working on the chemical composition combined with mechanical and thermal treatment, the Dual-phase steels combining crystalline phases
(ferrite and martensite) to consolidate both strength and ductile characteristics, that contain almost 10%-70% volume fraction martensite, where the important content of martensite increases tensile strength [1], which yield strength may attain of approximately 1000 MPa [2]. Generally, the Dual-phase steels production is achieved through controlled cooling followed by fast cooling, in such a way that austenite is transformed into martensite, which the transformation is carried out with cooling rates that are attainable on production lines and according good adjustment of the hardenability. Several investigation studies of impact steels have shown that the Dual-phase steels are beneficial for absorbing energy during crash scenario [3,4]. The TRIP steels are known by the change of balance between the crystalline phases during formability, which makes significant ductility while keeping a high strain hardening capabilities and high mechanical strength, their yield strength may attain of approximately 831 MPa [2], they are used for the automotive parts requesting a complex stamping. The TRIP steels have shown a resistance to stress fractures more than have dual-phase steels [5]. In the automobile sector, the use of this type of steels with high yield strength is not always evident, it takes an adaptation between part design and steel that could be considered. Indeed, although the dual-phase steels and TRIP steels combine resistance and deformability qualities, a material with 550 MPa of yield strength still has a lower deformation capacity than a lower carbon steel. This requires an adaptation of design and settle for thickness optimizing and less deep-drawing. On the other hand, cutting and stamping processes of high yield strength steels are more expansive and require major investments. That is why the low-carbon steels with 0.13% or less of carbon levels have been the most automotive steels used especially for body panels and structural components, justified by their excellent formability, weld-ability and low-cost of manufacturing. The processing of low carbon steels is ensured by heat treatment, for that a smaller quantity of solute carbon are retained in solution, which, throughout heating, allows carbon to propagate and pin dislocations. From a mechanical point of view, solute carbon move to the dislocations until a carbon concentration level that it precipitates and pins the dislocation [6]. A familiar problem during manufacturing of automotive parts is primarily the spring back, which modifies the part geometry after stamping process, more specifically in the instance of high strength steels. To address these problems, many numerical and experimental studies were carried out for development of new steel generations mainly based on ultra-low carbon (ULC) steels, specifically the bake-hardenable steels, which are produced with ultra-low carbon contents, approximately 0.002%-0.005%, with manganese levels of less than 0.25%, well known by their high elongations and by high strain hardening coefficients that are useful for complex geometry parts stamping with modest cost and correspond to the needs of automotive industry, notably the lightweight and strength parts design for today vehicles. The bake-hardenable steels are used for both automotive panels and structural stampings, their yield strength may attain a range of 193-373 MPa. The bake hardening effect on the indentation resistance is exceptional and it have been used for a long time ago through the indentation performance that it presents [7,8,9], it can offer superior resistance to both static and dynamic indentation, compared with other steel classes, due to their increased strength after baking [10]. The hardening gain from bake hardening effect increases yield strength in the order of 80-150 MPa [11]. The manufacturing process of bake-hardenable steels based on carbon stabilization in solution to be necessarily harden for elevated temperatures, particularly in the automotive paint lines. The present study is to investigate numerically the indentation performance of ultra-low carbon steels and bake-hardenable steels for automotive roof panel. The part design was modelled via CATIA V5 and evaluated by FE analysis using ABAQUS Software. The results showed that the bake-hardenable steel sheets present a good indentation strength without pronounced plastic strain.

2. Numerical Modeling

2.1. Materials
The material used in the present study was ultra-low carbon steel with and without bake hardening effect. Therefore, we have used two materials classes, ULC steel and BH180 bake hardenable steel.
used for automotive applications as sheets of 0.6 to 0.65 mm thickness. The plastic deformation description is provided by the power law constitutive equation:

\[ \sigma = E\varepsilon, \quad \varepsilon \leq \frac{\sigma_y}{E} \]  
\[ \sigma = K\varepsilon^n, \quad \varepsilon \geq \frac{\sigma_y}{E} \]  

(1) 
(2)

where \( \sigma \) is the stress, \( \varepsilon \) is the strain and \( K \) is strain hardening coefficient with \( K = \frac{\sigma_y}{E\varepsilon_y^n} \) and \( n \) is the strain hardening exponent.

The Mechanical properties of ULC steel and BH180 steel for roof panel are shown in table 1. The input true Stress-logarithmic Strain curve of ULC and BH180 steels used in ABAQUS are shown in Figure 1.

### Table 1. Material Properties of the ULC and BH180 Steels

| Property                          | ULC          | BH180        |
|-----------------------------------|--------------|--------------|
| Density, \( \rho \) (kg/m\(^3\))  | 7820         | 7820         |
| Elastic modulus, \( E \) (Mpa)    | 210000       | 210000       |
| Yield strength, \( \sigma \) (Mpa) | 180          | 280          |
| Poisson’s ratio, \( \nu \)        | 0.3          | 0.3          |
| Strain hardening exponent, \( n \) | 0.17         | 0.17         |

### Figure 1. True Stress-logarithmic Strain curve of ULC and BH180 steels used in ABAQUS

2.2. **Finite element analysis**

For simplification and reduction time CPU reasons, a shell finite element model, modelled and simulated using Abaqus software. Figure 2 shown the roof panel mesh achieved, boundary conditions and applied indentation loads. The roof panel thickness is 0.65mm.
For accurate results of investigated parameters, the mesh must be denser and consistent, to this end, we have adopted the four-node linear quad elements with shell element type (S4) and 5-5 mm of element size. The total elements number of finite element model is 62409, Figure 3 shown a close-up of the roof panel mesh.

![Figure 2. FE-model of roof panel for indentation analysis](image)

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![Figure 3. Close-up of the roof panel mesh](image)

**Figure 3.** Close-up of the roof panel mesh

3. Results and discussion

For best interpretation and indentation performance assessment of materials selected, parameters such as deformation, plastic deformation and displacement must be addressed. Figure 4 represents von mises stress distribution, equivalent plastic strain (PEEQ) and displacement for ULC and BH180 materials. As one can see in the simulation results, the maximum stress obtained from bake hardening steel may reach more important elastic deformation (290.8 Mpa Figure 4c) and less von mises stress distributed as that of ULC steel (210.5 Mpa Figure 4a). Plastic deformation parameter remains the main important parameter to indentation response analysis. Although the maximum stress for BH180 steel exceeds mildly the material yield strength, the plastic strain distribution is distributed locally with a maximum PEEQ which remains below 0.2% (Figure 4d). The maximum stress of ULC steel exceeds greatly the material yield strength, consequently, the plastic strain distribution is more important with a maximum PEEQ of 0.5041% (Figure 4b) which remains well above 0.2%. The maximum displacement of ULC steel (9.413 mm Figure 4e) is more pronounced as that of BH180 steel (6.657 mm Figure 4f).
Figure 4. Von mises stress distribution ULC steel (a); Plastic strain (PEEQ) ULC steel (b); Von mises stress distribution BH180 steel (c); Plastic strain (PEEQ) BH180 steel (d); Displacement ULC steel (e); Displacement BH180 steel (f)

Figure 5 shows the accumulated permanent displacement comparison as a function of indentation force. The accrued permanent displacement of two selected materials increases almost of the same value and is ending with a pronounced displacement of ULC steel with a maximum value of 3.75mm, and 3.25mm displacement value of bake hardening steel.

Figure 5. Accumulated displacement comparison of the ULC steel and BH180 steel
4. Conclusion
In this paper, static indentation of automotive roof panel was studied, we have used a shell finite element model using Abaqus software. For a better analysis of indentation response and selected materials performance evaluation for indentation resistance, we have chosen and interpreted important parameters such as deformation, plastic deformation and displacement, which have shown that the roof panel can reached a pronounced elastic deformation in using bake hardening steel than that of ULC steel, without plastic strain and less displacement. In the main, for the roof panel and other exterior automotive body, especially those being indented daily, it is advisable to use a bake hardening steels.

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