Numerical investigation of introduction of HFQ® process manufacturing of A-pillar part

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Abstract. To meet the challenges of the automotive industry in recent decades, engineers have responded with new advanced materials and new technological processes suitable to form the new materials. The appearance of aluminium and its alloys in the automotive industry was justified by its lower density compared to steels and by the weight reduction arising from it. The lower ductility of aluminium alloys with sufficient strength initiated the development of new innovative technology (HFQ®). This paper presents a numerical feasibility study using the AutoForm software system by comparing two technological processes, i.e. the Press Hardening of Steels (PHS®) vs. Hot Forming and Quenching (HFQ®) of aluminium alloys. The Thermo-Solver module of the AutoForm software system includes material card for the 22MnB5 steel grade but does not for the AA7075 high strength aluminium alloy. Therefore, the material parameters that are necessary for hot forming simulation by the AutoForm must be determined experimentally. For this purpose, the GLEEBLE 3500 thermo-mechanical simulator was used to determine the basic material properties with hot uniaxial tensile tests and hot formability tests were performed to determine the forming limits (FLC).

1. Introduction
The automotive industry has been facing more and more challenges over the last few decades due to the tightening of environmental and safety standards. Mass reduction of vehicles with greater security may be regarded as one of the prospective research area to meet these challenges. Therefore, nowadays an increasing development of high-strength metallic alloys can be observed. Among metallic alloys, high-strength aluminium alloys due to their low density compared to steel can be considered as the best alternatives for weight reduction [1]. However, their wider application has a serious limitation due to their lower formability properties.

It is well-known that the formability of metallic materials can be increased by increasing the temperature; therefore, it is a plausible solution to apply hot forming processes for manufacturing high-strength aluminium alloys. A number of research projects based on this principle have been designed in the recent years. It has been reported that the University of Birmingham and Imperial College London (ICL) jointly developed the Hot Forming and Quenching (HFQ™) process and later patented by Impression Technologies Ltd. (ITL).

Everyday work of design and process engineers working in the automotive industry cannot be imagined without the application of up-to-date numerical modelling software focusing on the mass reduction of the material. Therefore, one of the focal point of any technology to be introduced can be examined using this software prior to the physical production of tools. Therefore, a suitable forming process with technological accuracy is required for numerical modelling. Thus, the purpose of this
paper is to demonstrate how accurately the HFQ™ process can be modelled with one of the industry-leading numerical applications (AutoForm R8plus).

2. Numerical modelling of hot forming of sheet metal

The PHS® technology, have been used in mass production in the automotive industry for decades, requires its examination by numerical modelling. The developers of dedicated software for technology and tool design have faced a serious challenge. Their software which is basically suitable for modelling the cold forming processes of sheet metal had to be made able to model the thermo-mechanical processes. One of the biggest problem is that how the applied material models describe the change in material properties with change in temperature. The path to this can be followed in detail in the publications of several authors [2,3,4]. Most dedicated software successfully integrated Boron steels material model and PHS® technology into their systems by 2010. The AutoForm Thermo-SolverPLUS module in version R7 of the software, in addition to PHS®, can also be used to analyse the effect of cooling channels to further support tool design [5]. As a result of the processes discussed in the section 1, the automotive industry has shifted its attention to high-strength aluminium alloys and their forming technology.

2.1. Introduction of Hot Form Quench (HFQ®) technology

By the middle of the 2010s, using the research results of several projects, the HFQ® (Hot Form Quench) technology was ready for implementation in mass production in the automotive industry [6,7,8]. In parallel, software developers have turned their attention to numerical modelling of new technology (HFQ®). This was based on several authors’ publications on modelling the warm forming of 5xxx series aluminium alloys [9,10]. Although the results of the numerical modelling were consistent with those of the physical experiments, the automotive industry prefers 6xxx and 7xxx series aluminium alloys in mass production due to their higher strength properties.

The figure 1 shows the temperature-time diagrams of 22MnB5 (PHS® technology) and AA7075 (HFQ® technology) to compare the similarity of the thermal cycles to be implemented. The similarities are well recognizable because the shapes of the curves are same with only difference in the temperatures.

![Figure 1. Comparison of Temperature-Time Diagrams of 22MnB5 (PHS® Technology) and AA7075 (HFQ® Technology).](image)

The first step in the technology (1) is to heat the blank to the appropriate temperature. This means the austenitizing temperature (930 °C) for Boron steel and the solution heat treatment (SHT) temperature (485 °C) for AA7075 aluminium alloy. This is followed by transfer (2) from the furnace to the forming tool then tool closing and cooling in the tool (3). The last technological step in HFQ®
technology is ‘aging’ (4). Focusing on numerical modelling of the forming process the aging step (4) of HFQ® is not discussed in this publication. The technological steps of the PHS® on which the comparison is based in the AutoForm Thermo-SolverPLUS module are already well defined and the technological steps are the same as the HFQ® technology. Therefore, the differences between technological parameters and material characterisation need to be defined. The technological parameters are discussed further in section 3.

2.2. Material characterisation of AA7075

In AutoForm, for a material card, the material parameters must be given in the following grouping: basic properties, hardening curve, Yield surface and the forming limit curve. For the basic properties values of the AA7075 aluminum alloy, the material parameters of the alloy AA5086-H111 created for 2016 Numisheet Benchmark 3 were basically used [9]. These are the following: Young’s modulus (\( E = 7.1 \times 10^5 \) MPa), Poisson’s ratio (\( \nu = 0.31 \)), specific weight (\( \rho = 2.67 \times 10^3 \) MPa/mm), heat capacity (\( c = 2.42 \) mJ/m³K) and the conductivity (\( \kappa = 220 \) W/m/K). Although the temperature dependence of the Young’s modulus of 22MnB5 steel in the temperature range of the technology is not negligible, the temperature dependence of the Young’s modulus of AA7075 in the range of 20-350 °C was neglected.

The next group of input parameter is the material parameters related to the plasticity behavior (hardening curve). The dependence of hardening curve temperature and strain rate is a well-known phenomenon in sheet metal forming. The AutoForm software uses several mathematical models to describe the hardening curve, but it is difficult to find information on the temperature and strain rate dependence of the parameters. A more practical solution is to physically perform the necessary measurements and determine the hardening curves using mathematical extrapolation using the measurement points. The consortium partners of the LoCoMaTech project, examining the HFQ® technology of the AA7075 aluminum alloy from several perspectives created a temperature strain rate experimental matrix [11]. In line with this, hot uniaxial tensile tests were performed using a GLEE BLE 3500 thermo-mechanical simulator, and the results were compared in parallel at several consortium partners, which showed a good agreement with an acceptable difference.

Figure 2. Hot uniaxial tension test on GLEE BLE thermo-mechanical simulator and temperature dependence of hardening curves of AA7075 alloy at 1 s⁻¹ strain rate.

Figure 2 (a) shows the working area of the GLEE BLE thermo-mechanical simulator at the end of the hot uniaxial tension test. With the help of the nozzle visible behind the specimen, the homogeneous range of the temperature distribution of the middle part of the specimen heating could
be extended during the test. The distortion of the electrochemically prepared mesh on the surface of the specimen determined the strain distribution on the surface of specimen by DIC technique (Vialux AutoGrid®).

Using Swift approximation \[ \sigma = C \left( e_p + e_o \right)^m \] for the measurement points, the hardening curves could be determined. Figure 2 (b) shows the temperature dependence of the hardening curves determined at 1 s\(^{-1}\) strain rate. The table 1 summarized the values of Swift approximation parameters with temperature.

| Temperature, °C | C, MPa | \(e_o\), - | m, - |
|----------------|--------|---------|------|
| 350            | 165    | 0.01    | 0.03 |
| 400            | 114    | 0.01    | 0.04 |
| 450            | 83     | 0.01    | 0.05 |

Table 1. Parameters of Swift approximation.

The third major group of input parameters required to produce a material card are Yield surface-related parameters. The Barlat (1989) flow rule and their input parameters were used. For this, the anisotropy coefficients and their temperature dependence were required. Determination of the anisotropy coefficients at each test temperature from the measurement results of the hot tensile tests were investigated, but this had to be discarded due less number of measurement points. Finally, the Numisheet Bechmark anisotropy coefficient and its temperature dependences were used for the input material parameters [9]. The table 2 summarized the values of parameters Barlat (1989) flow rule as a function of temperature.

| Temperature, °C | \(r_0\) | \(r_{45}\) | \(r_{90}\) | \(r'_0\) | \(\sigma_b/\sigma_0\) | \(M\) |
|----------------|--------|--------|--------|-------|----------------|------|
| 20             | 0.71   | 1.08   | 0.73   | 0.937 | 0.985          | 8    |
| 150            | 0.63   | 0.97   | 0.66   | 0.893 | 0.983          | 8    |
| 240            | 0.60   | 0.88   | 0.67   | 0.763 | 0.763          | 8    |

Table 2. Parameters of Barlat (1989) flow rule.

Numerical modelling can be run by specifying the material parameters described above. During the numerical modelling of the sheet metal, the evaluation of the forming limit of the sheet is based on the forming limit curve (FLC). Further, in numerical modelling of cold forming process FLC basically depends on the sheet thickness and the strain path. But during simulation hot forming process, the dependence of the forming limit diagram on temperature and strain rate appears strongly.

The determination of the forming limit curve at room temperature is fixed by a standard (ISO-12004). As the geometrical dimensions are fixed in the standard, thus it is difficult to ensure an isothermal temperature distribution at elevated temperatures. Another difficulty is providing the die movement speed required for its often high strain rate. There were a number of imaginative solutions to the problem, but insisting on extending the standard test, each solution had to compromise more or less.

Our institute has developed a measuring device that enables high-speed die movement with the help of the GLEEBLE thermo-mechanical simulator, with continuous DIC strain measurement during the LoCoMaTech project. In addition, it maintains a quasi-isothermal temperature field during the measurement. Assembly of the measuring device is shown in Figure 3(a). The upper part of the measuring device contains the test specimen and active tool elements (punch and die) required for
testing and can be quickly connected to the rest of the measuring device. Thus, they can be heated together in a furnace with suitable thermocouples and quickly connected to the rest of the measuring device the test can be performed with a homogeneous temperature distribution. Figure 3 (b) shows the device in a fully assembled state during the test. This position allows continuous measurement of deformation based on DIC technique. Figure 3 (c) shows the dependence of strain rate of forming limit curve of AA7075 aluminium alloy at 350 °C based on physical measurements.

![Figure 3](image)

**Figure 3.** Measuring device and forming limit curves of AA7075 aluminium alloy at 350°C determined at different strain rates.

3. Numerical modelling of HFQ® process

The LoCoMaTech project investigated the potential automotive components whose technology can be economically changed from currently PHS® technology to HFQ® technology. Among the possible workpiece, an A-pillar component was chosen for numerical modelling investigation. The complete geometry of the A-pillar component was shown in the middle of Figure 4.

First a simulation of the A-pillar component according to PHS® technology using the AutoForm Thermo-SolverPLUS module was prepared. For this simulation, AutoForm 22MnB5 material card and standard parameters of PHS® technology and software default process settings were used. Subsequently, the blank material of the A-pillar component (from Boron steel to AA7075) and the manufacturing technology (from PHS® to HFQ®) was changed in the AutoForm Thermo-SolverPLUS module.

An important question is what kind of result variables we choose for the comparison of the numerical modelling results of the two technologies (PHS® and HFQ®). The first comparison is based on the distribution of the temperature field. As the forming temperature range of the two technological variants is significantly different in the two methods, the comparison based on the temperature distribution field was discarded.
An important criterion is that the component must have adequate strength properties, so the comparison should be made on the basis of the distribution of some strength characteristic. During PHS® technology, the blank was heated to the austenitic state then formed to a final shape in water cooled dies. The forming process combined with rapid cooling transforms the microstructure to nearly 100% Martensite. As a result, after the die opening, the workpiece gain its final strength properties. This phase transformation can be numerically modelled in AutoForm Thermo-SolverPLUS module so that the strength distribution can be analysed at the end of the modelling. In HFQ® technology, the final strength of the workpiece was not achieved after forming, but in the ageing step. The numerical modelling of the ageing process has not yet been solved in AutoForm Thermo-SolverPLUS and therefore the comparison of the two technologies based on strength characteristics had to be discarded.

From a practical point of view, major technological criterion for automotive sheet metal parts is the minimization of thinning measured or numerical modeled along the part. A generally minimum allowable thinning value is of -0.30 in the automotive industry. Therefore, the results of each simulation were compared based on the thinning of the workpiece.

AutoForm is basically practice-oriented software, so the AutoForm-Solver module automatically sets the finite element parameters. The Finite Element Solver use Implicit Solution with Elasto-Plastic Shell element type. The AutoForm-Solver for refinement of initial elements uses a procedure that is well-known h-method.

The technological parameters of HFQ® such as the initial temperature of AA7075 blank was set to 485 °C, time to die was 10 s during the transfer process and waiting time blank in tool was 3 s before ram motion. Combination of the pressure and gap dependent heat transfer coefficient was used during forming process. The theoretical background and the values used were given in Figure 4.

![Figure 4](image-url) AutoForm Thermo-SolverPLUS pressure and gap dependent HTC model.

Figure 5 (a) shows the critical area of component for thinning when was used a 1.2 mm initial sheet thickness 22MnB5 blank material for the simulation. The color scale determined that the thinning are above the required lower specification limit (LSL= -0.30).

Figure 5 (a) and (c) display the thinning results of the HFQ® simulations of the AA7075 aluminium alloy for different blank thicknesses. In the first version of the HFQ® technology, the same blank thickness as boron steel was used, but this resulted in smaller thinning values than the prescribed lower specification limit. Therefore, it can be concluded that the blank thickness must be increased to keep the required lower specification limit of thinning. Additional HFQ numerical modelling was performed by increasing the thickness of the AA7075 place setting (1.5 mm and 1.8 mm).
Table 3 summarizes the thinning and A-pillar component weight results for each technology variant. From Table 3, it can be stated that the A-pillar component made of AA7075 aluminium alloy with HFQ® technology can be competitive in terms of thinning compared to the traditional HPS® technology. It also shows that the A-pillar made from aluminium alloy AA7075 using HFQ® technology can only be produced with increased blank thickness if thinning is to be kept within the tolerance limits. However, the aluminium alloy component has almost 50% less weight.

Table 3. Comparison of PHS® and HFQ® technology variants.

| Blank material | Thickness, mm | Thinning, - | Weight, kg |
|----------------|---------------|-------------|------------|
| 22MnB5         | 1.2           | -0.28       | 1.15       |
|                | 1.2           | -0.42       | 0.42       |
| AA7075         | 1.5           | -0.37       | 0.52       |
|                | 1.8           | -0.29       | 0.62       |

4. Summary and conclusion

New materials and technological processes to increase weight reduction in the automotive industry have come to the fore in recent decades. The technology of materials with special properties has changed in the direction of hot forming sheet materials. At the same time, the extension of the numerical modeling possibilities of new technological methods has increased.

This paper presents a case study of using the AutoForm Thermo-Solver PLUS module for numerical modeling of HFQ® technology. Based on the numerical modelling of the presented A-pillar component forming process, it can be stated that AutoForm is capable of modeling HFQ® technology. The main challenge was to determine the temperature and strain rate dependent material parameters of the aluminium alloy AA7075. For this purpose, the GLEEBLE thermo-mechanical simulator was used to perform hot uniaxial tensile tests and forming limit diagram determination. New physical measuring equipment has been designed to determine the forming limit diagram. In conclusion, the AutoForm Thermo-Solver PLUS module provides a suitable environment for the numerical modelling of the HFQ technology using presented A-pillar component forming process.
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