Process simulation and experimental validation of Hot Metal Gas Forming with new press hardening steels

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Abstract. One field in the work of the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Chemnitz is industry applied research in Hot Metal Gas Forming, combined with press hardening in one process step. In this paper the results of investigations on new press hardening steels from SSAB AB (Docol®1800 Bor and Docol®2000 Bor) are presented. Hot tensile tests recorded by the project partner (University of West Bohemia, Faculty of Mechanical Engineering) were used to create a material model for thermo-mechanical forming simulations. For this purpose the provided raw data were converted into flow curve approximations of the real stress-real strain-curves for both materials and afterwards integrated in a LS-DYNA simulation model of Hot Metal Gas Forming with all relevant boundary conditions and sub-stages. Preliminary experimental tests were carried out using a tool at room temperature to permit evaluation of the forming behaviour of Docol 1800 Bor and Docol 2000 Bor tubes as well as validation of the simulation model. Using this demonstrator geometry (outer diameter 57 mm, tube length 300 mm, wall thickness 1.5 mm), the intention was to perform a series of tests with different furnace temperatures (from 870 °C to 1035 °C), maximum internal pressures (up to 67 MPa) and pressure build-up rates (up to 40 MPa/s) to evaluate the formability of Docol 1800 Bor and Docol 2000 Bor. Selected demonstrator parts produced in that way were subsequently analysed by wall thickness and hardness measurements. The tests were carried out using the completely modernized Dunkes/AP&T HS3-1500 hydroforming press at the Fraunhofer IWU. In summary, creating a consistent simulation model with all relevant sub-stages was successfully established in LS-DYNA. The computation results show a high correlation with the experimental data regarding the thinning behaviour. The Hot Metal Gas Forming of the demonstrator geometry was successfully established as well. Different hardness values could be achieved depending on the furnace temperatures and the investigated material. Hardness up to 620 HV could be measured on the component with a complete martensitic structure.

1. Introduction
Nowadays press hardening is an established technique in the fields of lightweight construction for the production of high-strength components. It is supposed, that the worldwide demand for press hardened components will increase by 100 % up to 480 million parts until 2018 [1]. This trend is also visible in the automotive industry: in current vehicle models the percentage of press hardened components corresponds approximately 45 % with rising tendency [2]. Additional saving potentials offer the usage of tubes and profiles formed by Hot Metal Gas Forming-Press Hardening (HMGF-PH). The
combination of press hardening and HMGF of tubes and profiles allows the fabrication of highly
complex closed profiles with very high stiffness, high strength and a high level of dimensional
accuracy. The linked process offers a great potential for lightweight construction because material-
and structure-lightweight Technologies are combined. Typical materials for press hardening are
manganese-boron steels such as PHS 1900, PHS 1300 or 22MnB5 [3], [4]. Currently under
development are for example Docol®1800 Bor and Docol®2000 Bor from SSAB AB, which are
investigated in this paper and provided from the company [5]. The superior scientific question is how
a numerical simulation has to be done for accurate prediction of forming behaviour and if Docol tubes
can be successfully shaped with this forming strategy in general. Docol 1800 Bor is a commercial
hardenable boron steel used for the automotive industry. This alloy contains a small percentage of
boron to improve the hardenability. This steel can be easily hardened and can often be used without
subsequent tempering. This alloy is used for press hardening of safety parts such as door impact
beams, bumper systems and B-pillar reinforcements. This steel grade has been designed to reach
tensile strengths of 1800 MPa after fast cooling. Docol 2000 Bor is a new press hardening steel alloy
developed by SSAB, which is currently introduced in the market. This alloy is able to achieve a tensile
strength of 2000 MPa.

There are several concepts for press hardening closed profiles which can be differentiated by their
active medium and cooling strategy. The ACCRA-Technology, developed by Linde + Wiemann
GmbH KG, uses air as active medium and cools down the preheated component by flooding both
component and forming tool with water [6]. Another technique is explained in [7] where, the above
austenitisation temperature heated closed profile is cooled down after the mechanical forming process
with a water spraying nozzle inside the profile. In contrast to that it is possible to use granulate as an
active medium, also, which is described in [8]. In [9] another variant is explained where an additional
quenching effect is generated by the usage of air nozzles which can cool down the preheated part
locally to ensure a selective increase of the component hardness. Fraunhofer IWU is specialized on
press hardening of closed profiles with the use of nitrogen as active medium and non-heated but
actively cooled forming tools. Thereby the preheated closed profile (above austenitisation
temperature) is inserted into the forming die and is formed out and cooled down simultaneously [10],
[11].

2. Hot Metal Gas Forming-Press Hardening – experimental investigations

2.1. Experimental setup

A demonstrator tool DP1 was used to form the provided tubes of SSAB AB with a diameter of 57 mm
and a wall thickness of 1.5 mm. The DP1 demonstrator geometry consists basically of a rectangular
profile, which is connected by a transition of a large radius R35 (see Figure 1). The most characteristic
edge of this profile shows variable radii that change axially from R14 into the smaller radius R10.

![Figure 1. Part geometry DP1 and forming tool.](image)

The associated tool consists of a monoblock in which the mould insert is secured with clamping
wedges. Both the mould insert and the sealing insert are made of conventional hot-work steel 1.2343
and have been hardened to 52 + 2 HRC. The axial force for sealing the component is applied via two
punches with a conical sealing cap, whereby only one punch is designed for inserting the active medium in this case. The tool for the DP1 demonstrator was equipped in the Dunkes/AP&T HS3-1500 hydroforming press at Fraunhofer IWU (see Figure 3). Using a Maximator DLE 75-2 high-pressure compressor the forming pressure was provided inside the experimental setup. In this test series an axial sealing force of 250 kN and a tool closing force of 2100 kN was adjusted. The tubes with x-tec ZS 4037 coating were initially heated and austenitized with a Nabertherm furnace (model N41/13) and transferred into the demonstrator tool manually (see Figure 2).

2.2. Process temperature and experimental design

Before running the actual forming experiments, preliminary investigations were carried out to identify suitable furnace soak times and to analyse the cooling behaviour of the tubes during transfer time. For this purpose Docol 2000 Bor tube temperature was measured from the beginning of the furnace heating up to the insertion of the tube into the tool by two thermocouple wires, one exactly in the centre of the tube and one on the outside. The received heating and cooling curves can be assumed to be identical for both materials. Running this testing procedure it was possible to initially obtain the associated forming start temperatures after transfer and press closing for four selected furnace temperatures (870, 910, 975, 1035 °C, see Table 1).

| Furnace temperature [°C] | 870 | 910 | 975 | 1035 |
|--------------------------|-----|-----|-----|------|
| Furnace time [s]         | 210 | 180 | 180 | 180  |
| Max. temperature in center of tube [°C] | 842 | 889 | 961 | 1013 |
| Transfer time [s]        | 10  | 10  | 10  | 10   |
| Forming start temperature [°C] | 769 | 796 | 855 | 896  |
| Internal pressure [MPa]  | 18.5, 37, 67 | 67 | 67 | 67   |
| Pressure build-up rate [MPa/s] | 20, 40 | 20, 40 | 20, 40 | 40 |

Based on this preliminary study the selected furnace temperatures were afterwards used for the prior HMGF-PH experiments without any temperature measurement, taking into consideration the $A_{C3}$-temperatures (Docol 1800 Bor: 847 °C, Docol 2000 Bor: 813 °C). Besides different forming start temperatures the experimental plan consists of the parameters maximum internal pressure and pressure build-up rate, which are empirical values or the maximum values achievable by the system technology (Maximator high-pressure compressor). A total of 13 Docol 2000 Bor tubes and 10 Docol 1800 Bor
tubes were formed during the testing procedure. For every combination of parameter minimum of one sample was investigated in test evaluation for thinning, hardening and microstructural analysis.

3. Thermo-mechanical FEM simulation of demonstrator process

3.1. Creating the material model from hot tensile tests

Initially austenitized hot tensile tests for different testing temperatures and strain rates obtained by the University of West Bohemia, Faculty of Mechanical Engineering, were used to create a suitable material model for thermo-mechanical forming simulations. All hot tensile specimens were thereby heated up with a defined heating rate, austenitized and cooled to the corresponding isothermal test temperature with a defined cooling rate. First of all the raw data were converted into true stress-true strain-curves for the two investigated steel alloys Docol 1800 Bor and Docol 2000 Bor. For each of the 21 combinations of strain rate (0.5, 5, 50 s⁻¹) and testing temperature (950, 900, 850, 800, 750, 680, 600 °C), several hot tensile tests were available as a data basis, upon which individual support points were averaged. The support points determined in this manner were then used as an initial basis for the mathematical approximation of the curves using the combined Swift/Hockett-Sherby approach to define the flow characteristics of the material at higher plastic strains for the simulation (see Figure 4).

![Figure 4. Temperature dependent true stress-true strain-curves for strain rate 0.5 s⁻¹.](image)

Regarding the strain rate sensitivity of both investigated alloys (see Figure 5) the realized hot tensile tests for certain strain rates were enlarged by extrapolation of the investigated dependency up to a quasi-static strain rate of 0.001 s⁻¹. Thus, each of the material models for Docol 1800 Bor and Docol 2000 Bor alloys consist of approximated flow curves for the investigated forming temperatures and the measured or extrapolated strain rates. All flow curve approximations were then integrated into LS-DYNA material models for each alloy. The combination of temperature and strain rate dependent material model establishes the basic preconditions for a precise thermo-mechanical simulation considering the real conditions of the HMGF-PH process which are characterized by strongly variable deformation rates under various temperatures.

Both materials generally show similar behaviour with respect to temperature dependency, strain rate dependency and, in particular, with respect to work-hardening capacity. Major differences in flow stress between the two materials only occur at lower temperatures (see Figure 4, 600-800 °C) or higher strain rates (see Figure 5, 50 s⁻¹). For these cases, the Docol 1800 Bor-flow curves are up to 20 N/mm² above the stress level of the analogous flow curves for Docol 2000 Bor. In view of the process simulation of HMGF-PH and based on the similarity of the flow curves of the two materials, comparable forming behaviour is expected, particularly at higher forming temperatures.
3.2. Forming simulation setup

For the purpose of validation, the forming tests on the demonstrator tool DP1 were modelled in the LS-DYNA simulation to compare the achieved forming results. To this end, a rigid-surface-based model consisting of a movable upper tool and fixed lower tool surface was first set up by extracting the CAD surfaces of the real tools and transfer them into FE-meshes (see Figure 6). The process-specific constraints were matched to the conditions for the real test for the sake of comparability. Therefore all relevant upstream process steps (tube handling and transfer, tool closing, holding in closed state while insertion of the sealing punches) were reproduced analogously to the experimental procedure. All of these individual simulation steps were carried out with a coefficient of friction of 0.35. For tube modelling a Belytschko-Tsay shell element formulation was used with an initial element length of 0.75 mm. Besides the exact modelling of the experimental situation, basic thermal constraints (heat transfer by convection and radiation, pressure dependent contact heat transmission, heat conduction) were modelled according to proven simulation approaches [12] as well. Taking all of these constraints into account ensures an accurate computation of inhomogeneous tube cooling effects, which occur due to varying tube contact situations during upstream process steps and also inside the HMGF-PH stage itself.

4. Results

4.1. Thinning measurement

Components from each furnace temperature, pressure build-up rate and internal pressure were first of all investigated by wall thicknesses measurement. The aim was to determine the maximum thinning value as a function of various process parameters and to gain experience regarding the material behaviour in general. After initial test measurements it was possible to confirm the hypothesis that Docol 1800 Bor and Docol 2000 Bor have a very similar forming behaviour and thus also nearly
identical thinning results after the same HMGF-PH process. For results of thinning, the wall thickness distributions were measured at Zeiss Prismo 3D coordinate-measurement machine at Fraunhofer IWU in two different sections: first, a radial section in the region of the maximum circumferential strain and second, an axial longitudinal section along the characteristic edge of the component (see Figure 8), whereby each section measuring comprises 2000 single measuring points along the defined contour. For all of the measured part sections a good repeatability could be achieved here with a deviation less than 0.1 mm between the tested parts. In general it has to be emphasised that no significant trend for one influencing variable, such as internal pressure or furnace temperature, could be determined for the case of thinning behaviour. As general examples for wall thicknesses in radial and longitudinal cross section, samples are shown in Figure 8. The plotted thinning distribution for Docol 1800 Bor shows a minimum thinning in radial section of 47 % (0.80 mm wall thickness) and in longitudinal section of 41 % (0.88 mm).

4.2. Hardness
For testing the component hardness, 10 components with different furnace temperatures, pressure build-up rates and internal pressures were selected. The measurement series should be used to check whether the selected parameters meet the required hardness at all areas of the formed components. When measuring the hardness of the components, a total of four areas of a cross-section are of interest. These areas are the large radius R35, the small radii R10 in two different positions of the part DP1 and also the flat area (Figure 7). The cross section considered for hardness tests is located in same radial section of radial wall thickness measurement. A total of 18 measuring points in flat area were recorded.

Highest average hardness values in the flat area can be identified for Docol 1800 Bor at 961 °C tube temperature (forming start temperature 855 °C) with 576 HV5 according to Figure 7. The components with a lower tube temperature of 889 °C show a significant decrease in hardness. In addition, very high tube temperatures above Ac3 can also lower the resulting hardness. This was observed with the component heated to a temperature of 1013 °C. The resulting hardness values for Docol 2000 Bor with higher carbon content show a different trend. Here the samples show higher hardness values with lower tube temperatures at 842 and 889 ºC in general. The component with a tube temperature of 961 °C has a hardness of approx. 620 HV5. Once again the sample heated to a temperature of 1013 ºC achieved lowest hardness. Since the largest values with a lower furnace temperature were determined with Docol 2000 Bor, it can be shown that too high temperatures or too long holding times over Ac3 causes a decrease in the hardness. Differences in internal pressure or pressure build-up rate were not noticeable.

![Figure 7. Average results of hardness tests in flat cross section area for different tube temperatures.](image)

5. Validation of numerical simulation
The first simulation results supported the hypothesis of slight differences between the two materials, as the forming simulations resulted in approximately equal thinning behaviours (see Figure 6). At the same time, the results provided a starting point for estimating the quality of the simulation model, and
specifically of the material model by comparing them with the experimentally measured data (see Figure 8).

The material model was afterwards calibrated based on the comparison of the achieved thinning results. The calibration of the model primarily focused on material-specific parameters, such as the general yield locus approach, the yield locus exponent or the work-hardening behaviour of the material at higher effective strains, since the temperature- and strain rate-dependent flow curves only form a data basis for the plastic material behaviour under uniaxial stress to a maximum effective strain of approximately 0.2. Several studies with different material models have shown that varied flow curve approximations for higher plastic strains does not considerably effect the thinning results. The most consistent results were achieved using a Hill90 yield locus combined with a reduced biaxial flow stress level compared to Mises yield-locus. However, the influence of the investigated yield-loci as well as the yield locus exponent in the general thinning behaviour during HMGF-PH is still relatively small.

Figure 8. Comparison of experimental data and simulation along two sections.

Figure 8 shows the comparison of the thinning results along the radial section for the demonstrator part using a LS-DYNA material model MAT243 (Hill90 yield locus). In general, acceptably consistent results are seen here, since the measured thinning curve is reproduced with a mean deviation of only approximately 4 %. The global thinning maximum (47 % for Docol 1800 Bor) is also calculated almost exactly for both alloys, which is particularly relevant for estimating the feasibility of the forming technology. Besides computation of thinning behaviour, thermal model characteristics and general tasks in the context of forming behaviour like form filling at certain HMGF-pressures could also be shown inside simulation with a good accuracy. Overall the quality of the simulation model and especially the material models is positively assessed, so that a feasibility estimation of HMGF-PH processes for Docol 1800 Bor and Docol 2000 Bor can be achieved with the modelling methodology presented.

6. Conclusion
Hot Metal Gas Forming of the new press hardening steels Docol 1800 Bor and Docol 2000 Bor was successfully established on the basis of various experimental investigations on a certain demonstrator part. At a sufficiently high forming start temperature of 842 °C, demonstrator parts were completely formed for both materials. Nearly the same results in thinning behaviour could be determined, which correlates with the small differences in mechanical material behaviour of the analysed hot tensile tests. Investigations of different tube temperatures, maximum pressures and pressure built-up rates have shown that no significant influence can be obtained on the thinning behaviour for the investigated experimental design. On the contrary, different component hardnresses can be achieved by varying
tube temperatures. If the component is heated in range of \( A_C \), the highest hardness values can be achieved, whereby lower temperatures lead due to an incomplete austenitized microstructure to lower hardness levels as well as higher temperatures due to grain growth. In general Docol 2000 Bor shows higher hardness values than Docol 1800 Bor because of the higher carbon content. Basically, the presented strategy of thermo-mechanical simulation and in particular the derived material models for both Docol 1800 Bor and Docol 2000 Bor allow an acceptable computation of the HMGF-PH process. As the comparison to the demonstrator parts have shown, thinning behaviour could be computed in a precise manner so that a suitable feasibility evaluation for industrial processes is possible.

7. Summary and outlook

Based on the results of the practical Hot Metal Gas Forming test series and the numerical simulations the studies on the new press hardening steels Docol 1800 Bor and Docol 2000 Bor will be continued with a new and innovative forming demonstrator tool. Therefore new developed hot-working steel from Rovalma S.A. and an integrated active tool cooling system will be used. During the design stage of the new tooling an improved measurement technology to analyse both part and tooling temperature will be implemented as well. By determination of the mechanical properties after Hot Metal Gas Forming with integrated press hardening, further knowledge can be used for the numerical investigation of the process. Future studies will include the simulation of cyclical and close-to-serial-production processes in combination with its validation by practical investigations.

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