Experimental modelling of materials properties and microstructure of new high-strength steels for press-hardening and hot metal gas forming

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Abstract. Press-hardening is a highly dynamic process that involves rapid temperature changes. These process aspects play a major role in microstructural evolution and mechanical properties. In order to develop any thermomechanical processing sequence, including press-hardening, materials models of the best possible accuracy are needed, if relevant results are to be obtained from FEM methods employed for designing metalworking processes. Therefore, relevant data on materials behaviour under real process conditions must be obtained experimentally. In one such experiment, as described here, PHS 1800 and PHS 2000 low-alloy sheets of steel were subjected to thermal exposure identical to the heating sequence for press-hardening, including the removal from the furnace and transfer to the tool. Heat treatment sequences were proposed which correspond to the thermal profiles in the actual process. The results were input into FE simulations of press-hardening. In the low-alloy steels, the selected heat treatment sequence led to strengths of more than 2000 MPa and elongation levels of approx. 9%.

Key words: Press-hardening, PHS 1800, PHS 2000, Material-technological modelling

1. Introduction

The automotive industry is one particular sector that increases the demands on the properties of formed sheet metal. In order to meet these demands, various methods are being developed, such as press-hardening. (Fig. 1). This article explores opportunities for altering the mechanical properties of final products and for accurately designing their final microstructures. Advanced methods of this kind might soon begin to bear on today’s production of sheet metal parts for the automotive industry and may considerably improve these parts properties [1, 2]. Among the very promising materials, there are the PHS steels from the company SSAB which deliver strengths around 2000 MPa along with elongation levels of around 10 %. The treatment of these steels was designed under the effiPRESS project (RFSR – CT-2015-00019).
Press-hardening is a dynamic process in which the blank is heated and austenitized in a furnace and then transferred to a tool to be formed and quenched in a single step (Fig. 2) [10]. The blank is cooled rapidly by the contact with the tool. The deformation and cooling rates lead to hardening microstructures, providing the desired mechanical properties, namely high strength and sufficient ductility [4, 5]. Such properties are of major importance to the automotive industry because they lead to improved passenger safety and to potential weight savings and the related operation efficiency [6].

![Figure 1: Number of press-hardened parts produced annually to meet demand [2, 3].](image1)

**Figure 2**: Schematic diagram of the press-hardening process.

### 2. Experimental Program

Two new UHS steels (ultra-high-strength) were specially designed for this experiment: PHS 1800 and PHS 2000. Despite their low alloy levels, they show potential for excellent mechanical properties (Tab. 1).

**Table 1**: Chemical composition of experimental materials declared by the manufacturer.

| Composition | C        | Si     | Mn       | P      | S     | B         |
|-------------|----------|--------|----------|--------|-------|-----------|
| PHS 1800    | 0.27 – 0.33 | Max 0.40 | 1.15 – 1.45 | Max 0.025 | Max 0.035 | 0.0008 – 0.0050 |
| PHS 2000    | 0.33 – 0.40 | Max 0.40 | 1.15 – 1.45 | Max 0.025 | Max 0.035 | 0.0008 – 0.0050 |

PHS 1800 and PHS 2000 were supplied in annealed and as-rolled condition, respectively. Their as-received microstructures consisted of ferrite and pearlite. The microstructure of as-received PHS
1800 showed signs of presence of globular cementite. By contrast, PHS 2000 contained lamellar pearlite and elongated ferrite grains which clearly indicated the rolling direction (Fig. 3). The as-received steels had distinct mechanical properties. The ultimate strength of PHS 1800 was 515 MPa, whereas that of PHS 2000 was 1070 MPa. In order to obtain comprehensive information on both materials, CCT diagrams were constructed using JMatPro software for designing the first processing sequences (Fig. 4).

**Figure 3**: Micrographs of as-received experimental materials. PHS 1800 with spheroidized perlite in the ferritic matrix after annealing. The microstructure of PHS 2000 was ferritic–pearlitic with lamellar perlite after cold rolling.

**Figure 4**: CCT diagrams of experimental materials constructed using JMatPro software (JMatPro, Release 9.0, Sente Software Ltd., 2016).

### 2.1. Data preparation for developing the material-technological model of the press-hardening process of experimental steels

For the purpose of characterizing the impact of the rolling direction upon mechanical properties and detecting any defects caused by rolling, the first step involved tensile testing of sheet metals in their initial condition in several directions (0°, 45°, 90°). In the next step, simplified press-hardening sequences were designed. These involved heating to 850°C, 900°C, 950°C and 1000°C and subsequent water and oil quenching. In these sequences, the holding times were varied. Between holding and
quenching, a pause was made in order to simulate the real transfer from the furnace to the tool. This pause took between 7 and 12 seconds, depending on the specimen shape (sheet or tube) and the instrument (Fig. 5).

These sequences were carried out in a thermomechanical simulator. They provided a basis for identifying sufficient holding temperatures for both materials. Based on these sequences, parameters for simulations of the real press-hardening process were found by iteration. The purpose was to achieve the desired properties of the material within the shortest time and at the lowest possible costs.

Figure 5: Schematic diagram of a simplified press-hardening sequence.

In PHS 1800, the temperature of 850°C was insufficient for full austenitization. The specimens contained ferrite and martensite. Although the extended holding time of 180 seconds – instead of 30 seconds – has indeed led to lower ferrite fractions, it was not sufficient for achieving a fully-martensitic structure. Full austenitization was only achieved by increasing the temperature to 900°C or more. Optimal mechanical properties were achieved with the austenitizing temperature of 900°C and isothermal holding for 180 s. After the austenitizing temperature was increased to 950°C and more, the ultimate strength decreased, most probably as a result of the onset of coarsening of the austenitic grain.

PHS 2000 became fully austenitized at a holding temperature as low as 850°C which was maintained for 30 s. In this steel, too, lower ultimate strengths of specimens were found when the holding temperature and time at temperature were increased (Fig. 7).

Higher holding temperatures led to lower strength characteristics in both steels (Fig. 6, 7). The likely cause is the on-set of grain coarsening. Considering the direction of rolling prior to quenching, it can be said that the results of tensile testing provided no proof of significant deviations in the case of individual rolling directions. The likely reason is the essence of the treatment of specimens which were fully austenitized before quenching.

2.2. Simulation of the real forming process

After evaluation and optimization of the parameters obtained from the simplified press-hardening process, parameters for preparing the material-technological model [11,13] of the real forming process were determined (Fig. 8). Specifically, this process was hot metal gas forming of tubes. Hot metal gas forming is used for shaping tubes by means of internal pressure of a working fluid [7, 12]. The resultant increase in the tube diameter of between 3% and 30% depends on the wall thickness and the steel type. Forming takes place in closed dies into which heated seamless or welded tube feedstock is placed. The advantage of this tube-forming process is that it does not require intricate-shaped dies and mandrels. The disadvantage is the working fluid pressure which may reach up to 800 bar [7, 8].
Figure 6: Schematic diagram of the simulation of the press-hardeninng process for tube forming.

Press-hardening is a highly dynamic process that involves rapid temperature changes. These process aspects play a major role in the microstructural evolution, and consequently in mechanical properties. In order to develop any thermomechanical processing sequence, including press-hardening, one needs materials models of the best possible accuracy, if relevant results are to be obtained from FEM methods employed for designing metalworking processes. Consequently, relevant data on materials behaviour under real process conditions must be obtained experimentally. For this reason, the steels under investigation were subjected to the same thermal schedule as the one applied to feedstock for press-hardening [6, 9].

The model consisted of heating the specimen to the desired temperature according to the actual heating curve. Two times at austenitizing temperature were used: 30 s and 180 s. This step was followed by a pause simulating the removal of the feedstock from the furnace and transfer into a tool. Afterward, deformation at various strain rates ranging from 0.5 to 50 s\textsuperscript{-1} was applied at various temperatures in the interval between 850 °C and 600 °C. Flow stress curves were obtained from these experiments. The flow stress curves which reflected the entire thermal exposure history for the press-hardening process were analysed and converted into true stress–true strain curves. Using numerical techniques, models for individual temperatures were constructed. This data became the basis for FE simulations of hot metal gas forming of welded tubes [5, 2].

3. Result and discussion

Information was obtained on the effects of austenitizing on final properties after quenching in oil and water. Oil-quenched PHS 1800 material had only become fully austenitized above 900°C. Lower processing temperatures cause proeutectoid ferrite to form, which considerably reduces strength properties. Optimum mechanical properties [14] were obtained with 900°C and isothermal holding time of 180 seconds in specimens with orientation parallel to the rolling direction – Rm = 1780 MPa and elongation A = 12%; in specimens perpendicular to the rolling direction – Rm = 1783 MPa and elongation A = 6%. Raising the austenitizing temperature above 900°C led to a decrease in strength (Fig. 7). Oil-quenched PHS 2000 material became fully austenitized above 850°C. In specimens that were parallel to the rolling direction, the maximum strength was 1950 MPa, along with elongation of A = 10% upon austenitizing at 850°C for 30 seconds. Similar mechanical properties profiles were obtained
in specimens which were perpendicular to the direction of rolling (Rm = 1950 MPa, A = 8%) (Fig. 8). As with PHS 1800, raising the austenitizing temperature above this value led to a similar trend which involved decreasing ultimate strength. Mechanical properties of water-quenched specimens of both experimental steels were similar to those of the oil-quenched ones. From the process viewpoint, both steels can be quenched in oil or water without any appreciable impact on the outcome.

**Figure 7:** Mechanical properties of PHS 1800 after simplified press-hardening.

**Figure 8:** Mechanical properties of PHS 2000 after simplified press-hardening.

4. Conclusions
The research results achieved up to now suggest that it is possible to get highly accurate models of technological behaviour of sheet metals during hot forming under the conditions of the press-hardening process. This model includes all aspects of microstructure evolution associated with the thermal history of the material. Furthermore, experiments showed the behaviour of materials under the specific
conditions of a hot forming process. This experiment incorporates the final rapid cooling in the tool. This rapid cooling is part of mostly used processes for the production of press-hardened parts. At the same time, information about the dependence of austenitization and austenitizing temperature on resulting properties after oil and water quenching has been obtained.

This collection of results enables a more sophisticated approach to be taken to designing various material processing routes involving press-hardening and other unconventional processes that rely on similar principles of formation of martensitic structures in thin-walled products of UHSS.

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