Microstructural and Mechanical Study of Press Hardening of Thick Boron Steel Sheet

J Pujante\textsuperscript{1}, E Garcia-Llamas\textsuperscript{1}, S Golling\textsuperscript{1,2}, D Casellas\textsuperscript{1,2}

\textsuperscript{1} Fundació CTM Centre Tecnològic, Plaça de la Ciència 2, 08243 Manresa (Barcelona), Spain
\textsuperscript{2} Division of Mechanics of Solid Materials, Luleå University of Technology, 971 87 Luleå, Sweden

E-mail: jaume.pujante@ctm.com.es, eduard.garcia@ctm.com.es, stephan.golling@ltu.se, daniel.casellas@ctm.com.es

Abstract. Press hardening has become a staple in the production of automotive safety components, due to the combination of high mechanical properties and form complexity it offers. However, the use of press hardened components has not spread to the truck industry despite the advantages it confers, namely affordable weight reduction without the use of exotic materials, would be extremely attractive for this sector.

The main reason for this is that application of press hardened components in trucks implies adapting the process to the manufacture of thick sheet metal. This introduces an additional layer of complexity, mainly due to the thermal gradients inside the material resulting in through-thickness differences in austenitization and cooling, potentially resulting in complex microstructure and gradient of mechanical properties.

This work presents a preliminary study on the press hardening of thick boron steel sheet. First of all, the evolution of the sheet metal during austenitization is studied by means of dilatometry tests and by analysing the effect of furnace dwell time on grain size. Afterwards, material cooled using different cooling strategies, and therefore different effective cooling rates, is studied in terms of microstructure and mechanical properties. Initial results from finite element simulation are compared to experimental results, focusing on the phase composition in through thickness direction.

Results show that industrial-equivalent cooling conditions do not lead to gradient microstructures, even in extreme scenarios involving asymmetrical cooling.

Keywords: Boron steel; Microstructure; Properties; Press Hardening; Thick Sheet Metal

1. Introduction
Since its first application in the early 80s [1], press hardened components have become widespread in the automotive industry. Hot stamped parts can be found particularly for structural and crash reinforcements, such as B-Pillars, A- and C- pillars and other components of the security cage [2, 3]. This is because of the very attractive combination of shape complexity, high mechanical properties and competitive cost that can be attained using this technology. An often-cited example is the Volvo CX90; press hardened steel composes 38 % of its body-in-white, the highest proportion in a passenger car [4]. This standardization has come hand in hand with the development of aluminised boron steel sheet [5]. Nowadays, direct press hardening of AlSi coated boron steel is the most common variant of the process.
A study by Schupfer et al [6] predicted a growth in demand of press hardened components during the 2010’s until a certain stabilization would be achieved around 2020, when press hardened components have become standard practice in the industry. As this point is approached, developments in press hardening push further from the traditional application areas: one example is the development of Zinc-coated boron steel with composition tailored to low-temperature forming [7].

One little explored application is the introduction of press hardened parts on trucks and heavy vehicles. While this application is mostly unexplored, the potential weight savings offered by press hardening in this industry is not to be ignored. However, press hardening of components for trucks requires processing sheet metal much thicker than that used in industry, with the resulting adjustments to the process window and its industrial particularities.

In this work, the basics of press hardening of thick steel sheet are explored. This includes a study of the austenitization of thick sheet metal and the effect of quench quality on the obtained microstructure and mechanical properties, with a focus in possible inhomogeneities through the thickness of the material.

2. Experimental methodology

2.1. Material

Material was received in the form of 6.9 mm thick sheet. Blanks were uncoated.

Chemical composition was determined by means of spectrometry; Table 1 shows the most relevant alloying elements on of the studied material. Values found resemble the ranges for DIN 22MnB5/EN 1.5528 steel, even though differences could be found with commonly reported values for commercial 22MnB5 steel [1] mainly in terms of C (lower) and Si (higher) content.

Material in state of reception was found to have ferritic-pearlitic microstructure, with ASTM grain size G11 and hardness 176 ± 4 HV1.

|          | C   | Si  | Mn  | Cr  | Al  | Ti  | B    |
|----------|-----|-----|-----|-----|-----|-----|------|
| 22MnB5  | 0.19-0.25 | ≤ 0.40 | 1.10-1.40 | 0.15-0.35 | 0.02-0.06 | 0.02-0.05 | 0.0008-0.0050 |
| Specimen | 0.18 | 0.42 | 1.20 | 0.242 | 0.043 | 0.029 | 0.002 |

2.2. Experimental methodology

2.2.1. Determination of critical temperatures

A TA Instruments DIL805 A/D dilatometer was used to obtain basic information about the critical transformation temperatures of the material. Tests were performed on cylindrical samples, 4 mm in diameter and 10 mm in length EDM-cut from the sheet metal.

Samples were heated up to 900 °C at different heat rates: 0.5, 1, 2.5 and 5 °C/s. Temperatures for beginning and end of austenitic transformation ($A_1$ and $A_3$) were noted. Austenitized samples were quenched in flowing helium for a cooling rate of 50 °C/s in order to determine martensitic transformation temperatures ($M_s$ and $M_f$).

2.2.2. Quenchability test

In order to study the quenchability of the material, a simple test was devised based on a modification of the Jominy test. A strip (25 mm wide, 100 mm long, 6.9 mm thick) was cut from the blank. The sample austenitized in a convection/radiation furnace (600 s total furnace time at 900 °C). The austenitized sample was then extracted and introduced in a recipient with tap water at approximately 15 °C, held vertically so that only the bottom tip was submerged. The lowest 11.6 mm of the strip were submerged in water in this manner.
2.2.3. Heat treatment of samples

Square samples 100 mm x 100 mm were cut from the 6.9 mm thick sheet metal blanks. Samples were introduced in a convection/radiation laboratory furnace in open (oxygen-containing) atmosphere at 900 °C. An average heating rate close to 1.5 °C/s was measured from the thermocouples. Heating rate decreased with temperature, moving inside the 0.5-1 °C/s range at temperatures higher than 800 °C.

Austenitized samples were extracted from the furnace and manually transferred for cooling, with transfer time of approximately 10 s. Samples were cooled in different conditions, summarized in Table 2. Water quenched samples (1-3) were quenched in water at room temperature. Samples 4 and 5 were transferred to a press with a flat die, where they were press quenched at two different load levels (27.5 and 5 MPa). Sample 7 was put between two small steel blocks, with no external pressure exerted. Sample 7 was allowed to cool in air. Finally, sample 8 was asymmetrically cooled: two stacked austenitized samples were introduced into the press under 25 MPa, resulting in each sample only being cooled from one side.

Cooling rates were calculated using the signal from thermocouples welded to the different samples. Due to the non-linearity of cooling curves, values reported in Table 2 correspond to average cooling rates calculated in the interval between 880-460 °C.

Table 2: Heat treatment conditions studied in this work

| Sample | Total furnace time | Cooling conditions                     | Cooling rate   |
|--------|--------------------|----------------------------------------|----------------|
| 1      | 480 s              | Water quenched                         | >100 °C/s      |
| 2      | 600 s              | Water quenched                         | >100 °C/s      |
| 3      | 1200 s             | Water quenched                         | >100 °C/s      |
| 4      | 600 s              | Press quenched (27.5 MPa)              | 17 °C/s        |
| 5      | 600 s              | Press quenched (5 MPa)                 | 12 °C/s        |
| 6      | 600 s              | Cooled between metal blocks            | 5.5 °C/s       |
| 7      | 600 s              | Air cooled                              | 1.2 °C/s       |
| 8      | 600 s              | asymmetrically cooled                  |                |

2.3. Sample analysis

Small samples were cut from the center of each heat treated specimen for cross-sectional micrograph analysis. Samples were mounted, ground and metallographically polished and etched using Nital reactive in 2 % concentration. In order to detect possible microstructural gradients, microstructure was studied by optical microscope in three different points: 1 mm from each surface and at the center of the sheet. Additionally, Vickers hardness was measured in each of these points using 1 kgf (HV1). Finally, tensile specimens were wire cut from each of the heat treated pieces and tested.

2.4. Finite Element Modelling

The commercially available finite element code LS-DYNA was used to model the experimental setup of the heat treatment process of thick blanks. A material model suitable for hot stamping processes where phase transformations are crucial was used. The material model was based on the work of [8,9] where phase transformation from austenite into its daughter phases is predicted based on works [10–12].
Modelling starts after austenitization, the blank temperature is initially set to 900 °C. The blank is modelled using shell elements, tools use solid elements and a rigid material formulation. To reproduce transfer from furnace to tool a holding time is added prior to quenching in the tool. During holding, temperature decreases caused by convection and radiation, both effects are included by boundary conditions. In continuation the sample is inserted into the tool and load is applied on the upper tool half to create pressure corresponding to experimental conditions.

3. Results and Discussion

3.1. Austenitization Studies

Dilatometry results are presented in Table 3. Austenitization start temperature $A_1$ did not appear to be significantly affected by heat rate within the studied range. A slight increase was observed for $A_3$, up to 40 °C higher at 5 °C/s than at 0.5 °C. In all cases, samples were fully austenitized before reaching 900 °C. Beginning and end of martensitic transformation were determined at approximately 440 and 260 °C, similar to values reported for 22MnB5.

Table 3: Beginning ($A_1$) and end ($A_3$) of austenitization, and start ($M_s$) and finish ($M_f$) of martensitic transformation measured at different heating rates. Cooling rate is 50 °C/s in all cases.

| Heating Rate (°C/s) | $A_1$ (°C) | $A_3$ (°C) | $M_s$ (°C) | $M_f$ (°C) |
|---------------------|------------|------------|------------|------------|
| 0.5                 | 752        | 843        | 439        | 260        |
| 1                   | 754        | 862        | 440        | 261        |
| 2.5                 | 758        | 872        | 438        | 256        |
| 5                   | 764        | 881        | 441        | 257        |

3.2. Influence of Austenitization Time

Specimens were kept in the furnace for different amounts of total time, in order to check the effect of austenitization time on material performance. From thermocouple measurements, it was possible to determine that 900 °C were reached in approximately 480 s. According to dilatometry studies, at that temperature the material is fully austenitized. Samples kept for 600 s have therefore remained approximately 120 s austenitized, and 720 s in the case of samples kept for 1200 s.

Homogeneity of austenitization was evaluated by measuring the hardness of the samples after different austenitization times: the aim was to detect if full hardness could be attained with short austenitization times. Results, summarized in Table 4 show a marginal increase in hardness with increasing furnace time. However, differences are too small to be considered significant with this single study.

The effect of austenitization time on grain growth was evaluated by checking austenitic grain size on samples austenitized for 600 s and 1200 s. Results are summarized in 4. Grain size did not appear to change significantly after this significant increase in austenitization time: ASTM grain size was determined as G 11 for all samples, just as for as received material.

In order to check for surface decarburization, cross-sections of the material were analysed close to the surface for samples 2 and 3. Decarburized layers were observed to reach up to 50 µm into the material in some zones, but the average depth of decarburization was close to 20 µm. This is in the same order but somewhat milder than observations from other authors.
for press hardening of uncoated boron steel (thin sheet), reporting decarburization of up to 60 µm [13]. Depth of decarburization was observed to be uneven through the sample.

Table 4: Characterization of samples austenitized for different times.

| Sample | Furnace time | Average hardness [HV1] | Austenitic Grain size | Decarburization [µm] |
|--------|--------------|-------------------------|-----------------------|----------------------|
| 1      | 480 s        | 433 ± 4                 | ASTM G 11             |                      |
| 2      | 600 s        | 439 ± 5                 | ASTM G 11             | 19.2 ± 2.4           |
| 3      | 1200 s       | 446 ± 6                 | ASTM G 11             | 24.1 ± 2.5           |

3.3. Quenchability test

In order to determine the quenchability of the material, a test based on the Jominy procedure was performed, as described in section 2. Results of this test are shown in Figure 1 a and b, depicting material hardness as a function of distance to the quenched end of the sample, and Figure 1 c-e, showing microstructures obtained in the core of the sample at different distances from the quenched end.

Hardness and microstructure measurements show that no significant differences can be found up to 4 mm from the quenched end. A progressive decrease in hardness can be observed from 5 mm away from the water quench zone. This can be explained to some degree of tempering of the recently formed martensite, as well as higher bainite contents in a mixed martensite-bainite microstructure. Finally, a sudden drop in hardness can be found 13 mm away from the water line, coinciding with the presence of ferritic-pearlitic microstructural elements.

3.4. Influence of cooling rate

The influence of cooling rate on mechanical properties was studied using the heat treated 100 mm x 100 mm specimens prepared as described in section 2.2.3. Results are summarized in Figure 2, showing selected microstructures corresponding to different conditions, and Table 5, summarizing mechanical properties obtained.

Average hardness was observed to slightly diminish with diminishing cooling rate. Water quenched samples reached the maximum hardness of 440 HV1. For press quenched samples (Sample 4, 27.5 MPa and sample 5, 5 MPa) a slight effect of loss of hardness with decreasing cooling pressure was observed. This could be related to the lower heat transfer attained at lower contact pressures, as reported in the literature [14, 15]. However, microstructure in these samples was still dominantly martensitic (Figure 2 a). Moreover, tensile test results were mostly equivalent for those samples, as well as for water-quenched specimens.

Material cooled between metal blocks under no pressure (sample 6) or air cooled (sample 7) experienced much slower cooling, resulting in ferritic-pearlitic microstructures mixed with bainite in the former. Mechanical properties were consistent with these microstructures.

Asymmetrically cooled material (sample 8) developed a dominantly bainitic-martensitic microstructure (Figure 2 c). Both hardness and tensile results were significantly lower than for fully martensitic samples. Finally, samples cooled in a metal block or in air experienced much lower cooling rates, resulting in presence of ferrite-bainite microstructure and low mechanical properties. Material in this state was mostly equivalent to as-received sheet metal in terms of microstructure and hardness.

It is relevant to observe that in no cases were through-thickness gradients of mechanical properties observed (Table 5). Even for the asymmetrically cooled sample the microstructure
was basically homogeneous, despite the considerably dissimilar conditions of the two sides of the blank. This indicates that heat conduction inside the blank is much higher than heat transfer to outer media. This way, temperature inside the blank is mostly homogeneous, even in this extreme case.

3.5. **FE Modelling of microstructure evolution**

Two different cooling scenarios were modelled: in-die cooling at high pressure and asymmetrically cooled specimens.

Figure 3 a shows result of the phase transformation modelling for a die-quenched blank.
Table 5: Hardness obtained in different cooling conditions.

| Sample | HV1, side 1 | HV1, center | HV1, side 2 | HV1, avg. | Rp0.2 [MPa] | Rm [MPa] |
|--------|-------------|-------------|-------------|-----------|-------------|---------|
| 2      | 446 ± 4     | 443 ± 5     | 430 ± 4     | 439 ± 5   | 1040        | 1305    |
| 4      | 432 ± 4     | 435 ± 4     | 427 ± 4     | 431 ± 4   | 1007        | 1354    |
| 5      | 421 ± 4     | 416 ± 4     | 417 ± 6     | 418 ± 4   | 1083        | 1313    |
| 6      | 224 ± 5     | 245 ± 7     | 214 ± 5     | 226 ± 8   | 431         | 712     |
| 7      | 172 ± 5     | 173 ± 5     | 170 ± 5     | 173 ± 5   | 368         | 563     |
| 8      | 367 ± 13    | 366 ± 16    | 371 ± 13    | 368 ± 7   | 929         | 1147    |

Solid lines correspond to the evolution at the surface of the sample, dashed lines show phase transformations in the core of the material.

Simulation of the die-quenched sample resulted in mostly martensitic microstructure with small amounts of bainite both at the surface and the core of the specimen, with no significant differences in microstructure between the two points. This result is in line with experimental trials.

Figure 3b shows the modelled microstructural evolution on the asymmetrically cooled sample at two different points: on the contact with the cooled tool (solid line) and on the contact with the second sample (dashed line).

Simulation predicted an almost fully bainitic transformation, with residual amounts of other constituents (<3%). In this case there was some discrepancy with experiments, where a mixed martensite-bainite microstructure was observed. Differences can be explained by need to refine heat transfer in the different interfaces and experimentally adjust the simulated CCT curve.

On the other hand, no significant difference was observed in the final microstructure for the two studied zones, even though the transformation is displaced in time. This correlates with experimental results, showing a mostly homogeneous microstructure through the thickness of the sample. This reinforces the observation that, even in this extreme condition, thermal history gradients as severe as to cause microstructural through-thickness variations do not appear.
4. Conclusions

In this work, the basics of press hardening of thick boron steel sheet were studied. Different cooling conditions were explored, including different press pressures and one asymmetrical condition, by means of experimental trials and FE modelling. The main conclusions that could be drawn from the study are the following:

- There is a slight influence of heating rate on austenitization. However, material was fully austenitized upon reaching 900°C for the range of heating rate attainable with this material.
- Austenization time had mild effect on the material. No significant growth of austenitic grain was observed in 1200 s furnace time. Inhomogeneous decarburized layer was observed, typically 20 µm thick and reaching up to more than 50 µm. Slight increase in depth was observed when increasing austenitization time.
- In the wide range of cooling conditions explored, microstructures obtained were homogeneous through the thickness of the material.
- Even in the most extreme case, comprising material only quenched through one side, the obtained microstructure showed no significant asymmetry between the two sides of the blank. However, microstructure and mechanical properties obtained are consistent with slower cooling. This was further reinforced by FE modelling.

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