Effect of heat treatment conditions on the fatigue resistance of press hardened 22MnB5 steel evaluated through rapid testing technique

S. Parareda, D. Casellas, D. Frómeta, E. Garcia-Llamas, A. Lara, J. Pujante and A. Mateo

1 Eurecat, Centre Tecnològic de Catalunya, Unit of Metallic and Ceramic Materials, 08243 Manresa, Spain
2 Luleå University of Technology, Division of Mechanics of Solid Materials, 971 87 Luleå, Sweden
3 CIEFMA-UPC, Campus Diagonal-Besós, 08019 Barcelona, Spain

sergi.parareda@eurecat.org

Abstract. Fatigue strength is considered as a crucial parameter for automotive applications subjected to cyclic loads during their long service life, as chassis parts. The high yield stress of press hardened steels poses them as good candidates for lightweight solutions with improved fatigue resistance. However, their high strength leads to an increase in notch sensitivity which can ruin the whole part's integrity. This behaviour was observed in previous works on press hardened steels, where their high fatigue strength was significantly affected by the surface conditions and by heat treatment conditions. Nevertheless, press hardening steels are still good candidates to manufacture complex geometry parts reaching high performance.

Aiming at increasing the existing knowledge on the fatigue behaviour of press hardened steels, this paper analyses the fatigue performance of boron steel (22MnB5) under different times austenitizing times. Fatigue resistance is evaluated using a novel rapid fatigue testing technique based on the stiffness evolution. The method permits a fast and reliable determination of the fatigue limit. Based on results obtained with this rapid testing method, the most suitable heat treatment to mitigate fatigue notch sensitivity and then achieving the best fatigue performance for chassis applications is discussed.

1. Introduction

In the last years, a wide range of advanced high strength steels (AHSS) has been developed to satisfy the automotive industry’s demands on lightweighting and passive safety. These steels have high mechanical properties that allow to reduce the body in white (BiW) mass and to improve the vehicle crashworthiness [1]. However, they present moderate ductility compared to conventional mild steels, which is related to reduced formability that limits the shape of the body parts. Although several new AHSS have been developed with improved formability [2], this limitation is solved by the press hardening process. The excellent formability and low flow stress of the press hardening steels (PHS) in
the austenitic region (900-950 °C) allows obtaining geometries with complex shape and high strength up to 1600 MPa after the quenching step without springback issues [3,4].

This material, traditionally used in BiW for passive safety [5], can be used in other applications, such as chassis parts, increasingly relevant in electric automobiles architectures or heavy-duty vehicles. However, its application to chassis components should address their key design parameters, i.e. the fatigue resistance and notch sensitivity. Unfortunately, scarce fatigue data is available in the literature for the most common PHS grade, the 22MnB5 steel. The available works show that the fatigue behaviour of PHS is governed by surface irregularities, as shear edge defects and cracks in the coating, that act as fatigue crack initiation sites [6–8]. Such effects can be mitigated by sand-blasting or shot-peening processes that smooth the surface and introduce compressive residual stresses at this zone, as observed in uncoated PHS and AHSS [9–11]. However, the fatigue strength of PHS may also depend on the microstructure of both the coating [12–14] and the bulk material [15], which strongly depends on the heat treatment conditions during the press hardening process. In this sense, the conventional heat treatment conditions accept variations in terms of temperature and austenitizing time that produce slight deviations on mechanical properties (UTS and YS) but that can be critical in fatigue strength, giving rise to a manufacturing issue not considered until now.

The goal of this work is to investigate the effect of the heat treatment conditions on the fatigue resistance of 22MnB5. The fatigue behaviour is evaluated in a short time through a rapid fatigue testing methodology based on the stiffness evolution. The ability of the rapid methodology to predict the fatigue limit is shown by comparing the obtained fatigue limit results to the ones from conventional procedures [16], for the heat treatment condition most widely applied in the automotive industry.

2. Material and experimental procedure

All the material studied in this work was extracted from the same coil of commercial Al-Si coated 22MnB5 sheet steel, 1.7 mm in thickness. In its as-delivered condition, it is a cold-rolled steel sheet with ferrite-pearlite microstructure and an Al-Si coating approximately 20-25 μm thick. The chemical composition is given in Table 1.

| Material | C  | Si  | Mn  | P  | S       | Al  | B       | Ti+Nb | Cr+Mo |
|----------|----|-----|-----|----|---------|-----|---------|-------|-------|
| 22MnB5   | 0.233 | 0.235 | 1.130 | 0.014 | <0.001 | 0.063 | 0.003 | 0.039 | 0.181 |

The press hardening process was performed at Eurecat lab-scale hot stamping line. To not over-expand the testing matrix, the austenitizing temperature was kept constant at 900 °C and 4 different values of dwell time were selected, three of them within the accepted process window for austenitizing treatment in industrial conditions (Table 2). As a result of the different dwell time, different coating microstructures and prior austenite grain sizes (PAGS) were obtained. The heated blanks were then transferred to a set of water-cooled flat dies, where the blanks were quenched to room temperature without imposed deformation. The temperature profile of the blanks was evaluated by using a K-type thermocouple welded onto the surface.

| Condition | T_s [°C] | t_h [s] | t_s [s] | t_d [s] |
|-----------|----------|---------|---------|--------|
| 390s      | 900      | 175     | 5       | 180    |
| 240s      | 900      | 175     | 65      | 240    |
| 390s      | 900      | 175     | 215     | 390    |
| 1800s     | 900      | 175     | 1625    | 1800   |
The microstructure was analysed on the through-thickness plane parallel to the rolling direction (RD) for each fully hardened sheet blank. The cross-sections were mounted, mechanically ground, and polished using colloidal silica suspension. Samples were etched in two different ways. The first, with a 2% nitric acid solution (Nital 2) to reveal the martensitic microstructure (Figure 1) and the coating Fe-diffusion layer. The second, with picric acid to show the prior austenite grain boundaries. The Nital etched samples were analysed in the ZEISS Ultrapluss Field Emission Scanning Electron Microscopy (FE-SEM) equipped with an Energy Dispersive X-ray Spectroscopy analyser (EDX). The picric acid-etched samples were observed using an OLYMPUS Light Optical Microscopy (LOM) to determine the PAGS according to ASTM E112 procedure [17].

Figure 1. a) Optical image and b) SEM image of the martensitic microstructure of 22MnB5 for the 390s condition.

Fatigue behaviour was evaluated using hourglass specimens following the ASTM E466 standard [18]. Specimens with a radius of 100 mm were machined by spark erosion at 90° concerning the RD and edge polished to specular finish. A drawing of the specimen geometry is shown in Figure 2. The fatigue limit, \( \sigma_e \), was defined at \( 2 \times 10^6 \) cycles. It was evaluated using the staircase or up-and-down method proposed by Dixon-Mood [16] for the 900 °C and 390s condition, the most widely applied heat treatment condition in the automotive industry. At least 15 specimens were tested at room temperature, using a stress ratio of \( R = 0.1 \) and at a frequency of 80 Hz. The obtained fatigue limit will be compared with results obtained by the rapid testing approach, to check its accuracy.

Figure 2. Hourglass fatigue specimen (\( K_t = 1.03 \)) with the polished edge (in red colour). Dimensions are expressed in mm.

The fatigue limits corresponding to the four heat treatment conditions were evaluated using the new rapid fatigue testing method based on the stiffness evolution (patent EP20382742). The method relies on the measurement of the fatigue damage through the determination of the specimen stiffness after each successive fatigue block [19]. The stiffness evolution is then plotted against the stress amplitude of each block and mathematically adjusted to determine the fatigue limit associated with the absence of damage, i.e. to the initial stiffness. The fatigue blocks’ length was 6000 cycles, with an increasing amplitude of 1% of UTS between each one. The maximum stress, \( \sigma_c \), for the stiffness determination, i.e. displacement measurement between two points fixed above and below the most stressed zone, was set at 15% of UTS. At least three specimens were tested for each heat treatment condition, all of them at room
temperature and using a stress ratio of $R = 0.1$. Tests were performed in a servo-hydraulic testing machine MTS 322 Test Frame, at a frequency of 30 Hz, equipped with a Digital Image Correlation (DIC) system GOM Aramis SRX for displacement measurements. The total testing time for one condition was 4h.

3. Results

Tensile properties for each heat treatment condition are given in Table 3. Results lie within the expected range of properties for 22MnB5 steels with a martensitic microstructure [3]. The effect of the heat treatment conditions is evident on the PAGS: as the dwell time in the furnace increases for a given temperature, the PAGS increases.

After the heat treatments, Al-Si coatings present the typical five-layer structure formed by alternating Fe$_2$Al$_5$ (sub-layers 1 and 3 in Figure 3c) with $\tau_1$ Fe-Al-Si intermetallic (sub-layers 2 and 4) and finally a Fe-based diffusion layer (sub-layer 5), according to Grigorieva et al [13]. Kirkendall voids in the coating are formed during the precipitation of intermetallic phases due to the different diffusion rates of Al in Fe, and vice-versa [20]. The intermetallic compounds or phases observed in the coating depend on the austenitizing parameters, which influence the diffusion kinetics of Fe, Al, and Si. Figure 3 and Table 3 show the influence of the austenitizing parameters on the thickness of the coating-substrate diffusion layer. Increased holding time leads to a thicker diffusion layer; additionally, $\tau_1$ layers grow in thickness at expense of Fe$_2$Al$_5$ intermetallic, tending towards a homogeneous $\tau_1$ coating if sufficient dwell time were reached. This is consistent with references in the literature [13,21,22].

![Figure 3](image_url)

**Figure 3.** SEM image of Al-Si coating for a dwell time of a) 180s; b) 240s; c) 390s; and d) 1800s.

The fatigue limit results from the rapid tests are reported in Table 3, together with the fatigue limit for the 390s condition obtained by the conventional staircase procedure. The 180s condition shows the lowest fatigue limit while the 390s condition displays the highest one. As expected, the fatigue behaviour
is governed by the surface condition, i.e., by the cracks in the coating (Figure 4). Thus, the structure of the coating has a direct impact on the fatigue resistance of the investigated steel. The 390s condition presents the best balance between tensile strength and fatigue resistance, followed by the 240s condition.

Table 3. Austenitizing conditions, prior austenite grain size (PAGS), Fe-diffusion layer thickness, yield strength ($\sigma_{YS}$), ultimate tensile strength ($\sigma_{UTS}$), fatigue limit determined by the rapid fatigue test ($\sigma_{e\text{-Rapid test}}$) and by the staircase ($\sigma_{e\text{-Staircase}}$) procedure, and fatigue sensitivity ($\sigma_{e} / \sigma_{UTS}$), for the four heat treatment conditions.

| Austenitizing | PAGS [\mu m] | Fe-diffusion layer [\mu m] | $\sigma_{YS}$ [MPa] | $\sigma_{UTS}$ [MPa] | $\sigma_{e\text{-Rapid test}}$ [MPa] | $\sigma_{e\text{-Staircase}}$ [MPa] | $\sigma_{e} / \sigma_{UTS}$ |
|---------------|-------------|-----------------|------------------|-------------------|------------------|------------------|------------------|
| 900ºC – 180s  | 3.8 ± 0.2   | 0.8 ± 0.1       | 1087             | 1575              | 579 ± 19         | -                | 0.37             |
| 900ºC – 240s  | 5.9 ± 0.4   | 1.5 ± 0.2       | 1289             | 1647              | 693 ± 42         | -                | 0.42             |
| 900ºC – 390s  | 6.9 ± 0.3   | 4.6 ± 0.9       | 1210             | 1594              | 716 ± 23         | 729 ± 53        | 0.45             |
| 900ºC – 1800s | 11.3 ± 1.2  | 18.1 ± 1.2      | 1186             | 1574              | 629 ± 24         | -                | 0.40             |

Figure 4. Fracture images showing the fatigue origins related to cracks in the coating (white arrows) identified for: a) 180s; b) 240s; c) 390s; and d) 1800s specimens.
4. Discussion
22MnB5 steel sheets should have a fully martensitic microstructure to ensure high properties with a yield strength above 1 GPa and ultimate tensile strength above 1.5 GPa [3]. However, the different variables introduced during the heat treatment could play a key role in the mechanical response of the produced component, especially on the properties related to the coating structure, such as fatigue strength. A clear example is given in this work, where although the four investigated conditions satisfy the strength requirements in terms of YS and UTS, the fatigue resistance is clearly reduced for two conditions. In order to reveal the reasons for this fatigue deterioration, the structure of the coating and the material substrate must be examined in detail after the press hardening process.

Refinement of PAGS is, in general, beneficial for the mechanical properties of Al-Si 22MnB5 [23]. However, it should be pointed out that this affirmation is not valid for very short austenitization times. Table 3 shows that the 180s austenitization condition offers the lowest tensile and fatigue strengths, despite having the finest PAGS among the studied samples. This fact is mainly related to the insufficient austenitization time, that leaves untransformed ferrite in the martensitic matrix [24]. Figure 5 shows the ferrite grains of the 180s condition, which are characterized by a polygonal shape and a deep etching response, as compared to the martensitic matrix.

On the other hand, the proper heat treatment in terms of a fully martensitic transformation leads to higher fatigue resistance, as is shown for the 240s condition. But the superior tensile strength increases the fatigue notch sensitivity, i.e., lower \( \sigma_e / \sigma_{UTS} \) ratio, which slightly reduces its fatigue strength below the 390s condition. The highest fatigue limit is found for the 390s condition due to a better balance between the PAGS and the Fe-diffusion layer thickness. Pujante [22] discusses a noticeable decrease in hardness in the Fe-based diffusion layer, compared to the intermetallic coating and martensitic substrate. Hence, according to Suresh [25], cracks nucleated in the brittle coating can be stopped in the soft Fe-layer improving in this way the fatigue resistance of the 390s condition.

This behaviour led the authors to investigate an extreme case with a very thick Fe-diffusion layer. A thick Fe-diffusion layer was obtained by increasing the austenitizing time up to 1800s. Although the cracks were stopped at the diffusion layer (Figure 3d), the 1800s specimen presents a low fatigue limit. The long austenitization time notably increased the PAGS, which penalize the mechanical properties of the press hardened steel [15]. A further comprehension of PAGS and Fe-diffusion can provide important knowledge in order to optimize the austenitization conditions for ultra-high strength combined with excellent fatigue resistance in PHS.

![Figure 5. SEM micrograph of the microstructure of 22MnB5 austenitized 180s. The white arrows indicate the untransformed ferrite.](image-url)
5. Summary and conclusions

In this work, the effect of the austenitization time on the fatigue strength of 22MnB5 press hardened steel has been evaluated. Even though all the evaluated conditions show similar values of tensile strength, fatigue strength is strongly influenced by the austenitizing process that has a crucial effect on the coating and substrate microstructure. A shorter or a longer austenitizing time, regarding the conventional one, leads to a decrease in the fatigue limit. It has relevant implication for the industrial production of fatigue dimensioning parts using PHS. The value of UTS or YS cannot be used to validate the heat treatment because the fatigue limit is more sensitive to austenitization time variations than YS or UTS. Additionally, the austenitization process has been optimized using tensile properties for crash resistance application. The optimum treatment parameters may be different for fatigue parts, they could be reached by balancing the PAGS and the Fe-diffusion layer thickness.

On the other hand, the fatigue limit calculated by the proposed rapid fatigue test correlates well with the value obtained through a well-accepted method as the staircase, which uses more than 15 specimens. It allows pointing out the rapid fatigue method based on stiffness evolution as a suitable methodology to estimate the fatigue resistance of PHS. The method is simple and expedient and does not require dedicated apparatus or complex data treatment. Thus, the technique is presented as an optimization tool to rapidly determine the effect of multiple process conditions on fatigue behaviour, looking for the best fatigue performance.

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