A fracture mechanics approach to develop high crash resistant microstructures by press hardening

Daniel Casellas[1,2], David Frómeta [2], Toni Lara[2], Silvia Molas[2], Pär Jonsén[1], Stefan Golling[1], Mats Oldenburg[1]

Abstract

Crashworthiness is a relevant engineering property for car parts. However it is not easy to measure at laboratory scale and complex impact tests have to be carried out to determine it. Crash resistance for high strength steel is commonly evaluated in terms of cracking pattern and energy absorption in crashed specimens. Accordingly, the material resistance to crack propagation, i.e. the fracture toughness, could be used to rank crashworthiness. It has been proved in a previous work by the authors, so the measure of fracture toughness, in the frame of fracture mechanics in small laboratory specimens, would allow determining the best microstructure for crash resistance parts. Press hardening offers the possibility to obtain a wide range of microstructural configurations, with different mechanical properties. So the aim of this work is to evaluate the fracture toughness following the essential work of fracture methodology for ferrite-pearlite, bainite, ferrite-bainite, martensite and martensite-bainite microstructures. Results showed that bainitic microstructures have high fracture toughness, similar to TWIP and CP steels, which allows pointing them as potential candidates for obtaining high crash resistance in parts manufactured by press hardening.

1 Introduction

Automotive industry players (steelmakers, part manufacturers and carmakers) are continuously looking for laboratory scale methods to measure crash behavior. Axial and bending crash tests are state of the art in steel development. Such tests are very expensive and time consuming which difficult innovation on materials and forming process for crash resistant parts. During the last years, many efforts have been put on correlating small-scale mechanical test results with large scale crash tests. Tensile tests characterize mechanical properties, but as shown in the past, the elongation values or the energy under the engineering curve are not appropriate to classify the crash behavior of steel grades. This is because they completely underestimates the post-uniform region from necking start to fracture [1] Alternative tests, such as bending test, are useful to predict, for example, bending-dominated failure that occurs with AHSS (Advanced High Strength Steel) grades during folding/bending in axial and side crash tests [2]. Recent works show that bending tests were more effective and accurate, than tensile elongation properties to understand crash in cold forming AHSS grades and in press hardened steels [3].

Axial and bending impact tests results are commonly evaluated in terms of deformation, cracking and the overall appearance of the specimens after crashing. Impact tests results for very high yield strength steels (above 800 MPa approximately) is quantified by an overall Crash Index (CI) for each deformed crash sample. The decrease in crash index CI with increasing crash intrusion depth (-*ΔCI/intrusion*) quantifies the crack propagation speed behaviour in crash testing. The lower this parameter, the better the crash tolerance against crack propagation in crash tests. This methodology has been implemented in several AHSS obtaining convincing results [1,3]. The CI depends on the number and length of cracks observed in the sample after the crash test [3]. Then, if crash behavior is dominated by crack initiation and propagation, it could be rationalized in terms of the material resistance to crack propagation, i.e. the fracture toughness. However, fracture toughness of AHSS is not systematically characterized, mainly because it is experimentally difficult to measure in thin sheets. Recently, the authors have proposed to measure fracture toughness in thin sheets through the application of the Essential Work of Fracture (EWF) methodology [4-7]. Such methodology can be successfully applied to characterize AHSS and press hardened steels. It has been proved to be useful to rank crashworthiness, so higher toughness values correspond to lower -*ΔCI/intrusion* ones [8].

Press hardening stands unique as technique to produce automotive components with tailored material properties at once. Tailored tempering is especially useful in components subject to crash deformation to maximize the energy absorption. Different microstructures can be generated in tailored tempering, depending on the cooling conditions. Thus, different amounts of martensite, upper and lower bainite and ferrite are usually obtained, that give rise to different mechanical properties and crashworthiness. The good correlation between fracture toughness evaluated by means of EWF and axial crash resistance will be here used to evaluate the potential of different microstructures obtained by press hardening to be used in crash resistant parts.

2 Materials and experimental procedure

The material used in the present investigation is the low alloyed boron steel 22MnB5, with a thickness of 2 mm. In as delivered condition, 22MnB5 shows a homogeneous distribution of pearlite in a ferritic matrix. The material is coated with an AlSi layer which protects from oxidation during heat treatment and corrosion during service life.

For the present study rectangular samples with dimension 240x40 mm were cut perpendicular to the rolling direction of the blank. These samples underwent five different heat treatment procedures with the aim of producing different phase content:

- Steel M: fully martensitic microstructure-
- Steel B: bainitic microstructure.
- Steel BM: mixed microstructure consisting of bainite and martensite.
- Steel FB: mixed microstructure consisting of ferrite and bainite.
- Steel FP: microstructure with ferrite and pearlite.

All samples underwent the same austenitization routine. In order to achieve full austenitization samples were placed in the center of a furnace heated to 900 ºC, the total time in the furnace was five minutes. A ferritic microstructure is achieved by air cooling to 650 ºC, inserting the sample into a second furnace were it is held for three minutes. After completed holding time the samples are air cooled. The two furnaces procedure is used because of high cooling rates small blanks exhibit in air. A pure bainitic microstructure is obtained by isothermal transformation of austenite in a tool heated to 430 ºC. Samples are after austenitization transferred to the heated tool, after tool closure a constant pressure is applied. Samples are held for two minutes in the tool and followed by air cooling. A mixed microstructure is achieved by combining afore mentioned processes. Samples are transferred from austenitization into the second furnace and held for one minute, in a subsequent step the sample is transferred to the tool and held for two minutes followed by air cooling. During the complete heat treatment process temperature is measured using a thermocouple spot welded onto the side of the sample.

Microstructure was revealed following standard metallographic procedures. Samples were polished and chemical etched with Nital and Lepera reagent to detect and quantify Bainite, Martensite and Ferrite, after observation of 15 frames of 255x250 µm working with an image analysis software. Samples were analyzed by light optical microscopy (LOM) and scanning electron microscopy with a field emission gun (FE-SEM). Vickers hardness was determined for each sample by applying 10N in the center of the specimen. Conventional axial tensile tests were performed according to EN-ISO6892-1.

Fracture toughness was experimentally evaluated by means of the EWF methodology developed by Cotterell and Reddel [8]. DENT (Double Edge Tensile Testing) specimens were tested with initial ligaments ranging from 7mm to 16mm. All specimens have a sharp crack, nucleated by fatigue testing on notch root machined by electro-discharge machining. The detailed description of the experimental procedure can be found in references 7 and 8. From the EWF tests the fracture toughness is represented by the essential work of fracture, w_e. By definition and as proved by many works, w_e is equivalent to the elastoplastic fracture toughness measured in *J-integral* tests.

3 Results and discussion

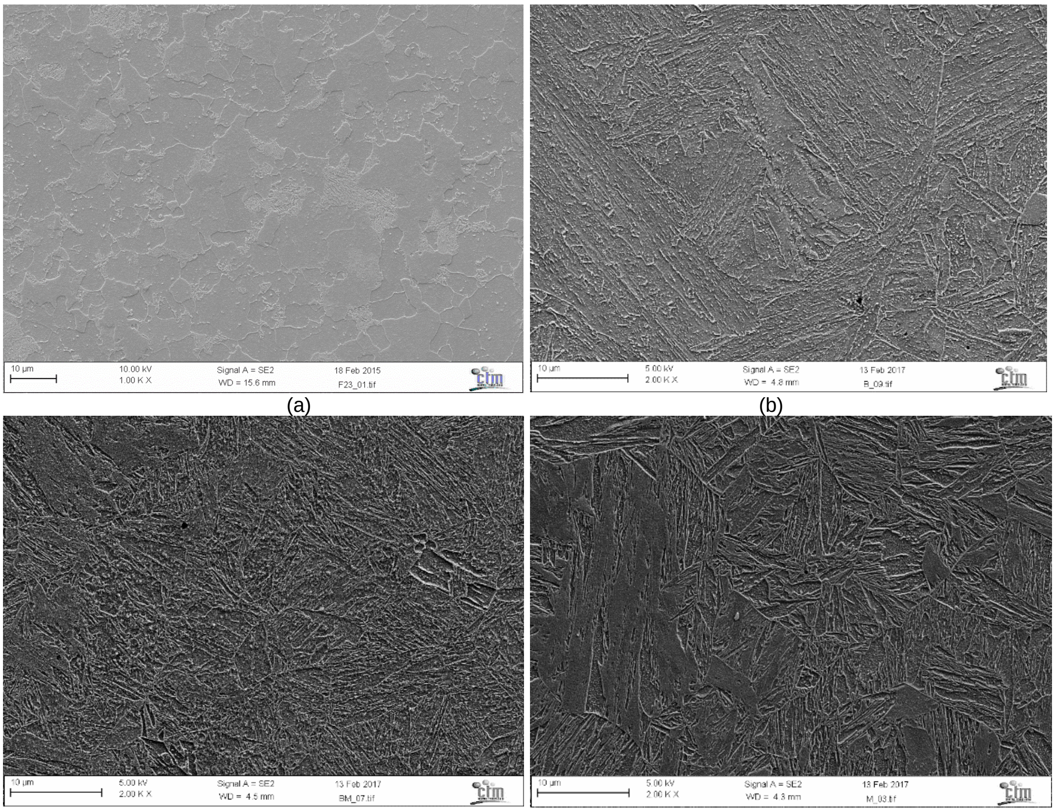
3.1 Microstructure and mechanical properties

The microstructure of the studied materials is shown in figure 2 and the amount of the different phases is shown in Table 1. Material F consists of a mixture of ferrite and pearlite. Material B is mainly bainite, with some martensite islands. Material FB consists of a mixture of ferrite and bainite with some island of retained austenite (less than 3% in mass content). Material FB is a mixture of bainite and martensite. And material M is fully martensite. Hardness Vickers for each material is shown in Table 1. Tensile tests results are shown in figure 2. Hardness and tensile test values are in the expected range for ferrite, bainite and martensite, with the exception of material BM. It shows higher hardness and yield strength than fully martensitic microstructure. Such hardness increase is explained in mixed martensitic-bainitic microstructures by rearrangement of internal residual stresses [9].

Table 1: *Phase content in each material (volume contents in %) and Vickers microhardness (HV1).*

Material	Pearlite	Ferrite	Bainite	Martensite	HV1
FP	26 ± 1	74 ± 1	-	-	196 ± 5

FB	-	40 ± 2	60 ± 2	-	240 ± 3
B	-		90 ± 3	10 ± 4	329 ± 3
M	-	-	-	100	466 ± 5
BM	-	-	40 ±5	60 ± 5	494 ± 3



(a) (b)

(c) (d)

Figure 2: *FE-SEM image of studied microstructures: (a) Ferrite-Pearlite. (b) Bainite. (c) Bainite-Martensite. (d) Martensite.*

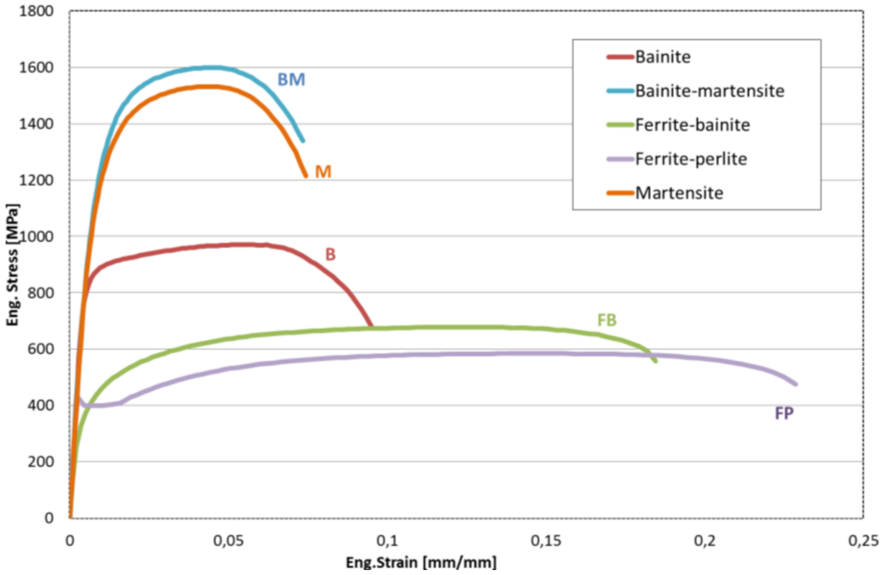


Figure 2: *Stress strain curves for the studied microstructures.*

3.2 Fracture toughness and crash resistance

Fracture toughness values evaluated by means of the EWF methodology, w_e, are shown in figure 3. As expected, fully martensitic microstructure (material M) shows low toughness. The lower value corresponds to the mixed microstructure BM, confirming the brittle behavior of this microstructure. Ferrite-pearlite has high toughness, as expected by their high amount of ferrite, meanwhile the mixed ferrite-bainite microstructure (FB) show an intermediate value. The toughest microstructure is the bainitic one, with a very high toughness value, similar to that measured in TWIP steels [5, 8].

The measured w_e values are plotted in figure 4 together with other AHSS against the crashworthiness measured in terms of the *-ΔCI/intrusion* (extracted from reference 8). The linear relationship between both parameters is valid for steel grades with high yield strength (>800 MPa), so it can be stated that FB and B microstructures show higher crash resistance than fully martensite microstructures (M) meanwhile the brittle behavior of BM ones does not recommend them for crash applications. FB and FP microstructures have low yield strength so their crash behavior can not be estimated from toughness measurements. Fully bainite microstructure shows promising properties since w_e, and hence crashworthiness, is high and similar to TWIP and CP steels, that have a well-known high crash resistance.

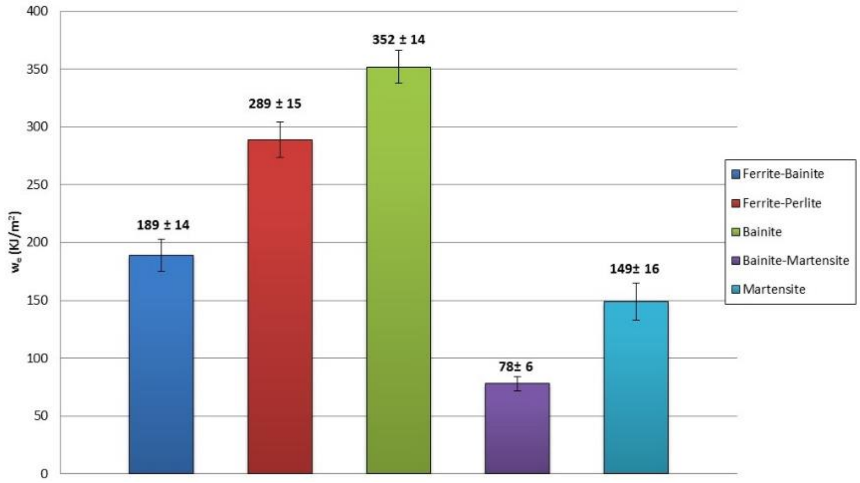


Figure 3: *Fracture toughness, in terms of w_e, for the studied microstructures.*

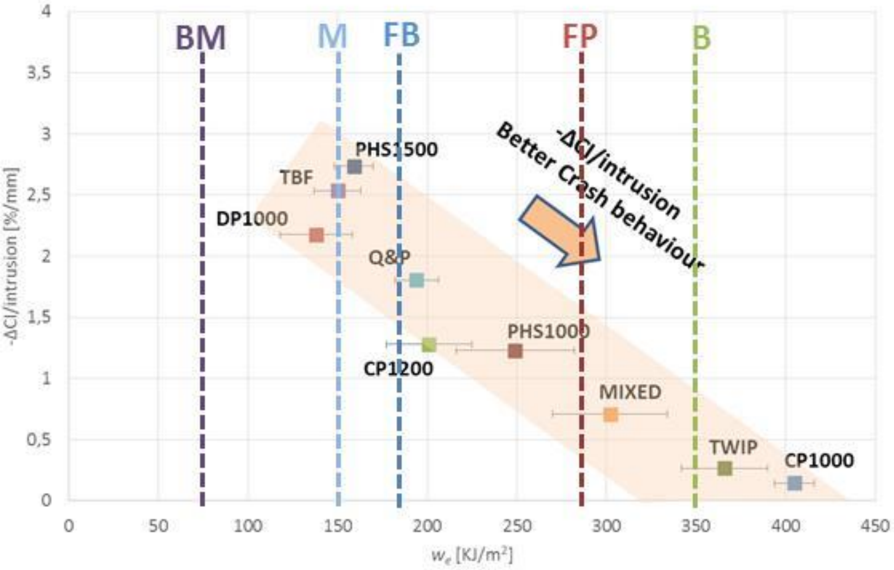


Figure 4: *Fracture toughness, in terms of w_e, against crashworthiness, in terms of -ΔCI/intrusion (data extracted from reference 8).*

4 Conclusions

In the present work, the fracture toughness, in terms of w_e, has been evaluated for different microstructures obtained by press hardening. Results show that bainitic microstructures have a very high toughness, comparable to TWIP or CP steels. According to previous results, showing a good correlation between fracture toughness and crashworthiness, bainitic microstructures are an interesting option to improve crashworthiness in press hardening. Further work should be carried out to assess which one of the different types of bainite microstructures (upper, lower or a mixture of those) gives the highest fracture toughness.

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Affiliation

[1] Division of Mechanics of Solid Materials, Luleå University of Technology, 971 87 Luleå, daniel.casellas@ltu.se

[2] Fundació CTM Centre Tecnològic, Plaça de la Ciència 2, 08243 Manresa, Spain, daniel.casellas@ctm.com.es