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Circular boron steel: a case study on high performance materials for a zero emission automobile industry

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Abstract. The European automotive sector is under pressure to transform into a zero net emission industry. This involves lightweight, highly efficient vehicles, but also zero emission structural materials. At the same time, a steel industry with automotion as its main customer faces a similar conundrum; it is only natural that this synergy is explored. One of the possible ways this need can be solved is by producing the high performance sheet steel consumed by the Auto industry through scrap-intensive Electric Arc Furnace (EAF) routes, saving an approximate 1.5 tCO2/tsteel compared through the integrated steelmaking route. However, in order to do this, the effect of *Residual* or *Tramp* elements inherited from the scrap needs to be considered into the downstream process and use phase. In this scenario, hot stamping of Boron steel sheet presents itself as an excellent use case. This process has become a mainstay in lightweight, high performance safety cage components in passenger cars. It is also gaining traction into light transport vehicles and trucks, and all future trends point to stable usage in the future. Transformed through hot stamping, boron steel shows incredible flexibility to cover different usage scenarios, all while having a simple chemical composition and reasonable cost. And as an added benefit, forming at high temperature bypasses many of the difficulties posited by the presence of residuals affecting springback and formability. This work shows a preliminary study on the concept of circular boron steel for automotive applications, produced by EAF instead of blast furnace. First, sources of scrap commonly used in steelmaking are analyzed to determine the residual elements and inclusions present in this raw material. From this study, studies have been performed to determine the effect on the steel CCT of the residuals with highest impact (in this case, Mo, Cr and Cu). Finally, an industrial cast has been produced and rolled into 4 mm thick sheet, such as it is being used in components like bumpers or in light trucks. Subject to common heat treatments, this material has shown performance on par with commercial, blast furnace products. Results show that scrap-intensive EAF production of Boron steel is possible, and that the impact of moderate amounts of residual elements can be acceptable in this application.

Keywords: Circular economy / electric arc furnace / press hardening / recycling / steel

1 Introduction

The European automotive industry faces a two-pronged challenge: on the one hand, the need of using advanced materials to reduce weight while at the same time maintaining or increasing performance; on the other hand, the need to drastically reduce carbon footprint and foreign dependency associated to the materials themselves. Available, recyclable and making use of existing knowledge and infrastructure, structural metals and steel in particular are naturally suited to this job. In particular, Advanced High Strength Steel sheet offers an attractive trade-off between strength, formability, affordability and light-weighting potential; and, out of those, press hardened steels have set themselves as the reference technology for safety cage applications since the 2000s [1].

However, steel is in its own turn one of the industrial sectors most affected by the 2050 European goals of sustainability and decarbonization [2]. Current steelmaking processes are considered to be very near their thermodynamic limits [3]. Therefore, relevant improvements in energy efficiency are subject to a deep change into the way steel is made.

From the point of view of CO_2 emissions, the carbon footprint associated to the steelmaking process can be dramatically reduced by switching production from the Blast Furnace – Basic Oxygen Furnace route to

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Table 1. Reference composition of grade 22MnB5.

C	Si	Mn	Al	Cr	Mo	Cu	B
0.22	0.25	1.20	0.4	0.30	0.005	0.07	0.030

scrap-intensive Electric Arc Furnace; sector data estimates an approximate 0.23–0.3 tCO_2/tsteel for EAF, vs. 1.8–2.2 tCO_2/tsteel in the integrated route [4].

However, producing sheet steel through the EAF route is non-trivial. In fact the EU currently serves the virtual totality of its sheet metal market with BOF products. This is mainly due to the presence of unwanted alloy elements in the scrap, dubbed *residual* or *tramp* elements, which are inherited by the recycled product. These elements affect the composition of the produced steel and modify its characteristics.

This was in fact the subject of many studies since the 1980s [5]. The scenario in steel recycling is relatively simplified by the fact that most alloying elements can be readily oxidized into the slag [6]. However, even when using this possibility, some elements do remain dissolved in the steel melt, notably Cu and Sn, but also Co, Mo, Ni or W.

Residual elements can have averse effects on steel properties. For instance, segregation to grain boundaries can impact properties such as hot ductility and formability [7]. quenchability Hardenability and metallurgical transformations can be affected by the presence of elements in solution [8] as well as interact with intended alloying elements. Finally, precipitates forming in the steel matrix [9] can affect sheet metal formability in cold forming operations. This latter reason is one of the main concerns in sheet metal forming, and one of the explanations on why scrap-based EAF steel production is usually dedicated to long product, as opposed to flat formats product.

Out of these unintended alloying elements, copper has been singled out as a limiting factor in steel recycling due to its mixing in post-consumer scrap. This has been posited as early as 1997 [10], with more recent studies [11,12] confirming the trend with specific data from the European Union. In particular, current vehicle scrap is estimated to yield and approximate 0.3–0.4% Cu, while sheet metal applications typically set Cu tolerance under 0.08%.

In this work, production of high performance sheet metal for automotive uses is explored, centering in the case of press hardening steels.

Press hardening, also known as hot stamping, is a non-isothermal forming process for sheet metals, where forming and quenching take place in the same process step [1,13,14]. In direct press hardening, blanks are austenitised at a temperature between 900 and 950 °C for 4–10 min in a furnace. The austenitised blank is then transferred to a set of cooled dies where it is formed in a single stroke. During this step, the cooled dies quench the formed component at a cooling rate between 50 to 100 °C/s, ensuring full martensitic microstructure. The total cycle time including transfer, forming and quenching typically takes 15–25 s. The result of this is a dominantly martensitic microstructure with Ultimate Tensile Strength of up to 1500 MPa, shaped in complex morphologies morphology that is only possible thanks to deformation taking place in hot, austenitic state.

Use of press hardening allows producing lightweight components with very high mechanical properties and complex shape while avoiding the problems, such as spring back on the component or damage including fracture on the tools, associated to cold forming of Ultra-High Strength Steels (UHSS). For this reason, press hardened components have mainly found use in structural and crash reinforcement components for the automotive industry [15]. The most commonly used press hardening material is aluminised boron steel sheet, most typically of the 22MnB5 grade [1].

Hot stamped steel is though to be an interesting use case for circular economy. For high-performance cold stamping steels, the effect of residual elements needs to be taken into account possibly for each batch of material, as it will have implications on formability, strain hardening or springback [16]. In press hardening, due to forming taking place at high temperature, the possible loss of cold formability generated by residual elements is no longer a problem, while strain hardening and springback are minimized. On the other hand, however, the effect of residual elements on quenchability hardenability through the distortion of CCT curves becomes a relevant issue.

To study this, in this work scrap from different sources typically used in EAF steelmaking is analyzed qualitatively and in terms of chemical composition, with the aim of determining the most common residual elements. Laboratory casts are produced using different contamination profiles, and the resulting material studied in terms of metallurgical transformations, in order to understand how the presence of residual elements affects the press hardening process. Finally, an industrial cast is produced with a moderate contamination profile, to verify that service properties of Boron steel could be obtained though the recycling route.

2 Experimental methodology

2.1 Reference grade

This work is centered around a low carbon Boron steel grade equivalent to Material no. 1.5528 under standard DIN EN 10083-3. This is a common grade in long product applications such as bolts and screws. However, in the last 20 years it has experienced a surge of use in sheet metal format, as it is the reference material for press hardening process [1,14]. In this process, this material is commonly referred to as 22MnB5, with approximate chemical composition as described in Table 1. This Boron steel is most commonly delivered as cold rolled 1–2 mm thick sheet

hot dip coated in Aluminum-10% Silicon, although variants exist as hot rolled, uncoated thick sheet [17] or even galvanized.

2.2 Analysis of scrap

Scrap from different *Packages Sorts* or internal categories was analyzed to ascertain its composition and characteristics. Three scrap packages sorts were studied, labeled *Pre-Consumer A*, *Pre-Consumer B* and *Post-Consumer*. These three packages sorts are used to produce scrap mixtures to be introduced in the Electric Arc Furnace, together with small amounts of DRI, master alloys and other minor inclusions.

For each of the scrap packages sorts, a Big Bag of material was procured, taking care that the content was representative of a typical sample of material. In order to do so, a methodology reproducing the work of DaSilva et al. [18] was followed.

Material in these bags was manually analyzed, by extracting a representative sample to identify its main constituents and detect typical contaminants. This allowed obtaining a general idea on the variability of the material and the kind of fragments present, as well as getting a qualitative evaluation about the presence of contamination or dirt. This will be discussed in Section 3.1.

Afterwards, chemical analysis was performed on scrap fragments. As the scrap consisted mainly in ferrous alloy fragments (mainly sheet metal), 10 fragments were taken from each packages sort to perform Optical Spectroscopy. As the material had been sorted in three bins from each of the Big Bags, fragments were taken at random, 3 or 4 from each of the bins. Average chemical composition of each scrappackage sort was calculated using the measured values.

2.3 Experimental casts

2.3.1 Laboratory casts

The main aim of this paper is to determine the effect of residual elements on the metallurgy of a steel produced from recycled material. In order to do so, laboratory-scale casts were produced with different levels of contamination (Sect. 3.2).

Casts were performed using a Vacuum Induction Melting furnace. Melting was done in a 75% Alumina – 25% Silica crucible, at a vacuum level of 2–10 mbar, using pure master alloys to better control chemical composition.

After casting in a sand mould, samples were heat treated for 2 h at 950 °C for homogenization, and finally air cooled. Each of the casts was approximately 8 kg in weight. The top 4 kg were discarded were discarded as a riser, and samples were extracted from the "safe" bottom part of the ingot.

These cast samples were hot forged to break the casting structure and force recrystallization, obtaining a microstructure closer to a rolled/wrought material. To accomplish so this, samples were austenitized in a furnace at 1250 °C for 600 s, transferred to a hydraulic press and hot deformed to approximately 60% reduction.

2.3.2 Industrial cast

A full-size cast was produced in an industrial Electric Arc Furnace in the CELSA-Global Steel Wire facilities in Santander (Spain). A 100 t cast was produced, cast and hot rolled into round format, and finally hot rolled into a flat strip 4 mm thick.

2.4 Determination of continuous cooling transformation curves

Continuous cooling transformation (CCT) were obtained for each of the cast materials, using a TA Instruments DIL805A/D dilatometer.

For laboratory casts, studies were performed on cylindrical samples, 4 mm in diameter 10 mm in length, wire cut from the hot deformed ingots described in the previous section. For industrial material, studies were performed on prismatic samples,5 mm wide and 10 mm long, with thickness equal to the 4 mm thickness of the available strip.

To obtain CCT curves, samples were austenitized at 930 °C for 300 s; these austenitization conditions were selected as representative for the industrial press hardening process [1,17]. Cooled rates used were 1, 5, 10, 20, 50 and 100 K/s. Works in press hardening literature cite 20–30 K/s as the usual critical cooling rate for 22MnB5 [13], and therefore these values were considered to be representative for variants of this process. Phase changes were obtained through dilatometry data, and verified through microstructural analysis (Optical Microscopy) and hardness measurement (HV1).

3 Results and discussion

3.1 Scrap analysis

The available scrap consisted in three different standardized scrap packages sorts available within the CELSA group. Two of these packages sorts, labeled in this work as *Pre-consumer* consisted essentially of refuse produced in industrial metalforming processes, while lot *Post-Consumer* consisted in assorted shredded steel fragments from different formats, including sheet, wire and shredded components.

Basic analysis was performed by manually sorting a sample of scrap fragments from each of the categories.

Pre-Consumer A and *B* consisted mostly in sheet metal fragments. Pre-Consumer B scrap was particularly clean and homogeneously sized, representing a "premium" package sort of sheet metal forming scraps. Most fragments corresponded to trimmings and refused blanks, in all cases showing little damage or contamination. *Post-Consumer A* had similar overall aspect, but also included some deformed or winkled blanks, and showed overall more surface oxidation and contamination, including dirt and oil gunk on the surface of the parts. Still, in general terms, both preconsumer scrap packages sorts presented relative homogeneity and cleanliness, and consisted mainly in press floor scraps with only exceptional nonferrous contamination.

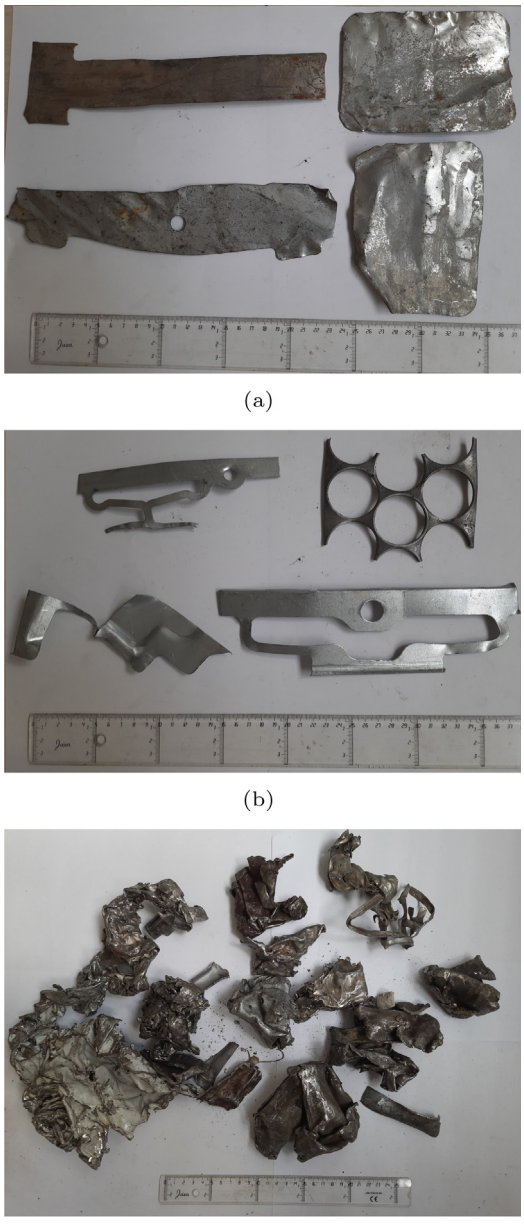
These ackages sorts could be equated to classes E2, E6 and E8 of scrap ("*New scrap*") according to the European Steel Scrap Specification [19].

On the contrary, *Post-Consumer* scrap was highly inhomogeneous, including sheet metal fragments, wire, bolts, tubes and massive parts. All these fragments were highly deformed (consistent with shredding) and showed characteristics typical of post-consumer scrap: many fragments were painted, welded or otherwise showed signs of coming from components in service. Moreover, contamination was significant in this scrap category including: small rocks and arid, small aluminum fragments and copper wire, in addition to dirt and grease. This scrap could roughly correspond to European norm E40, corresponding to shredded post-consumer scrap with tolerated amount of copper up to 0.25% in weight [19]. Interestingly enough, the scrap sample taken from the bin bag and exposed in Figure 1c includes an approximate 6 g of Cu on 3 kg of material. While anecdotal, this proportion is close to the 0.3% Cu in typical vehicle shredding scrap described in [11]. This serves to illustrate how little amount of Cu is needed to reach the commonly established limits for sheet metal applications.

For each of the scrap packages sorts, an analysis was performed to determine the approximate range of chemical composition to be expected. Ten steel fragments were extracted at random from each category, and subject to analysis by means of OES. The average of these measurements is reported in Table 2.

Results in all cases point to low C, low alloy steels. *Pre-Consumer A* scrap was particularly low-alloy, showing only moderate amount of Mn and low levels (under 0.1%) for all major alloying elements. *Pre-Consumer B* showed higher variability, and also higher average levels of alloying elements. For this scrap lot, some fragments were found with significant levels of Mn (up to 3%, for an average of 1.55% in the measured fragments), Cr over 0.5% in two of the 10 studied fragments and moderate levels of Si (0.20%), and including 1 (out of 10) fragments with detectable Mo (0.2%).

Finally, *Post-Consumer* scrap showed only mild alloying, with overall composition being lower alloy than *Pre-Consumer B*. However, in this case it must be noticed that the main source of contamination is not in the steel scrap itself, but rather in the inclusion of small nonferrous fragments mixed within the scrap.



(a) (b) (c)

Fig. 1. Representative samples of the different scrap lots a) Pre-Consumer A; b) Pre-Consumer B; c) Post-Consummer.

3.2 Experimental casts

3.2.1 Definition of experimental casts

Based on the analysis of scrap in Section 3.1, it was decided to produce small experimental casts with an increased amount of residuals.

The decision was based on the analysis of scrap presented in the previous section, together with the the state of the art.

The first cast was produced with an excess Chromium (Cr+ in Tab. 3). This is due to the presence of high Cr fragments in package sort *Pre-Consumer B*. While Cr does oxidize into slag [6], when processing steel with intended Cr content measures are taken to limit oxidation. This could lead to excess Cr in some scenarios. A target level of 0.45% Cr was chosen for this cast.

The second experimental cast used excess Molybdenum (Mo+). This is thought to rarely be a problem, as Mo is an expensive alloying element used in special steels and only marginally present in the scrap. However, Mo does not typically reduce into slag, meaning that Mo content can only accumulate when recycling. A level of 0.1% Mo was chosen for this cast.

The final cast was produced with high level of Copper (Cu+). This is due to the difficulty to avoid Cu inclusions in post-consumer scrap, combined with the practical impossibility of eliminating Cu from the melt during steelmaking.

Table 2. Average composition in wt% corresponding to each scrap package sort (average from 10 fragments/package sort extracted at random).

	C	Si	Mn	P, S	Cr	Mo	Al
Pre-Consumer A	0.06 ± 0.04	0.08 ± 0.11	0.45 ± 0.64	<0.01	0.07 ± 0.02	<0.03	0.04 ± 0.01
Pre-Consumer B	0.09 ± 0.04	0.22 ± 0.14	1.55 ± 1.00	<0.01	0.33 ± 0.02	<0.04	0.07 ± 0.05
Post-Consumer	0.06 ± 0.07	0.04 ± 0.08	0.47 ± 0.36	<0.01	0.09 ± 0.1	<0.03	0.04 ± 0.07

Table 3. Experimental casts; *target composition* and actual composition obtained. In all cases, P and S are kept below 0.015%; N below 0.006%.

Id	C	Si	Mn	Al	Cr	Mo	Cu	B
Base (Tgt)	*0.22*	*0.25*	*1.20*	*0.04*	*0.30*	*0.005*	*0.07*	*0.030*
Base(Actual)	0.20	0.31	1.22	0.03	0.34	0.001	0.071	0.023
Mo+ (Tgt)	*0.22*	*0.25*	*1.20*	*0.04*	*0.30*	***0.1***	*0.07*	*0.030*
Mo+ (Actual)	0.19	0.31	1.28	0.03	0.33	**0.06**	0.076	0.030
Cr+ (Tgt)	*0.22*	*0.25*	*1.20*	*0.04*	***0.45***	*0.005*	*0.07*	*0.030*
Cr+ (Actual)	0.19	0.31	1.30	0.03	**0.51**	0.001	0.077	0.030
Cu+ (Tgt)	*0.22*	*0.25*	*1.20*	*0.04*	*0.30*	*0.005*	***0.4***	*0.030*
Cu+ (Actual)	0.21	0.31	1.24	0.03	0.32	0.001	**0.39**	0.030

A level of 0.3% Cu was chosen, based on the expected levels in post-consumer scrap according to the consulted literature [10–12].

The different experimental casts are described in Table 3, including the target composition and the actual composition achieved. Differences are basically due to oxidation, and also yield of the master alloys used particularly for Mo.

From each cast, risers were discarded and samples were extracted out of its defect-free zone. These samples were subject to hot forming, to induce deformation and recrystallization and to turn the casting structure, not representative of a hot rolled material, into a microstructure more similar to a wrought product.

The result of this process is exemplified in Figure 2. This figure shows the initial casting microstructure, compared to a sample subject to austenitizing at 1250 °C, 60% reduction in a hydraulic press, and subsequently austenitized at 930 °C and slowly cooled (1 K/s) into a near-equilibrium Ferrite-Pearlite microstructure. Even though the obtained structure does not show as strong directionality as a rolled product, grain size and morphology as well as some Pearlite banding is indeed representative for a Boron steel grade in as-produced state.

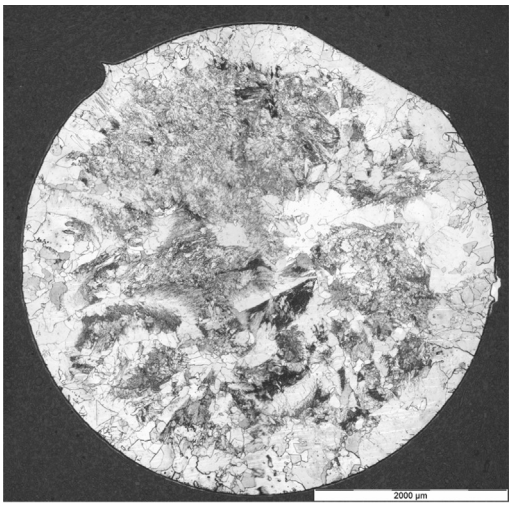
3.2.2 Effect of residual elements on the CCT curves

The effect of the residual element additions on material quenchability hardenabilitycan be very graphically seen in Figure 3. This series of figures includes the CCT curves obtained for each of the contaminated casts; the CCT obtained from the *Base* cast is superimposed in red.

Results are consistent with the knowledge in state of the art. In all cases (Cr, Mo, Cu), the addition of residual elements above the expected composition results in an outwards shift of the CCT curves (to the right). This is a well-known effect of the three studied elements [20], all of them being widely reported to enhance steel quenchability hardenability. It is still interesting to note that the total amount of these additions is moderate, and still leads to significant impact.

For the studied application of press hardening, this enhanced quenchability hardenability is not directly detrimental, and could actually be argued to be an advantage. When hot stamping, the steel needs to be cooled to complete martensitic transformation at a velocity beyond its critical cooling rate. Failure to do so results in insufficient quenching and leads to quality problems, from insufficient mechanical properties to warping [21]. This can be caused by a variety of reasons, with tool adjustment issues due to wear or misalignment being the most common. A material with a somewhat increased quenchability hardenability can help in smoothing these imperfections and reaching full quench even in the presence of small tool imperfections.

On the other hand, some applications of hot stamping include generating "soft zones" with lower strength and increased toughness. This can be accomplished through different routes, including tailored heating and martensite tempering [13,17], where CCT curves are not important. However, some soft zones are generated by differential cooling, in which some zones of the component are cooled slowly using different means: in this case, distortion of CCT curves could indeed impact the final properties obtained.



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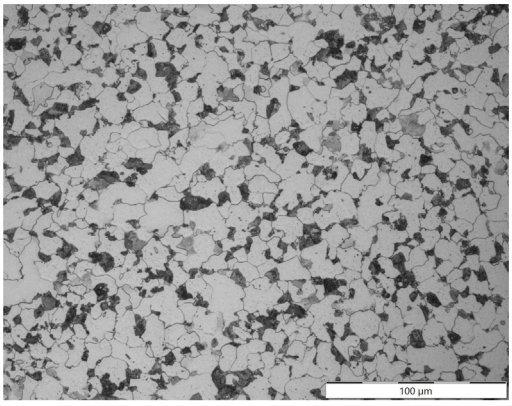
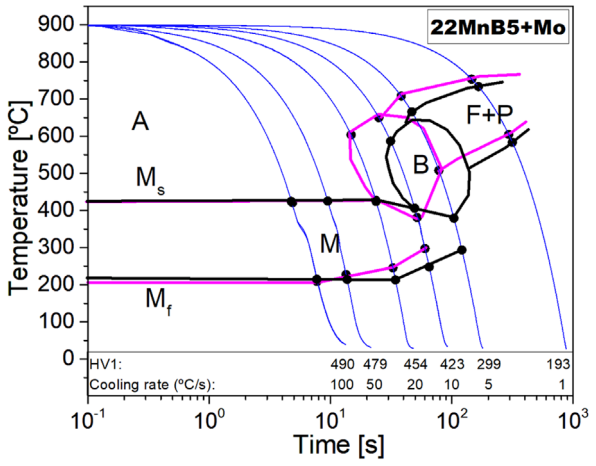


(b)

Fig. 2. Effect of hot deformation on the microstructure of Laboratory Samples. Images corresponding to *Base* cast *a*) As Cast; *b*) After 60% hot reduction, austenitization at 930 °C and slow cooling.

Finally, it must be noticed that the hot stamping process is an exception in sheet metal forming, as the forming takes place in austenitic state and the final heat treatment is obtained during the process. For cold forming materials, changes in quenchability hardenability may significantly affect how the steel microstructure develops during rolling and treating, with a direct impact on its behavior during forming; this has already been identified as a potential issue in steel recycling [16]. Indeed, CCT changes observed in this work could translate into a relevant impact on a cold forming grade, leading for instance to higher than expected Martensite content in a DP or CP grade, and therefore to higher than expected mechanical properties, press force and springback. While this does not discard recycled sheet metal from being used, it does point to the need of adaptive forming processes to be able to successfully process it.



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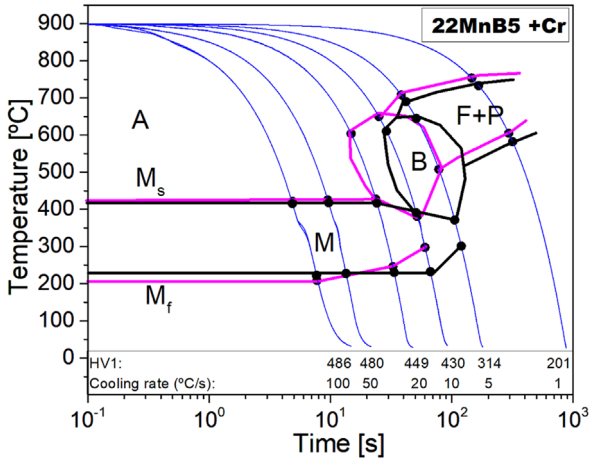

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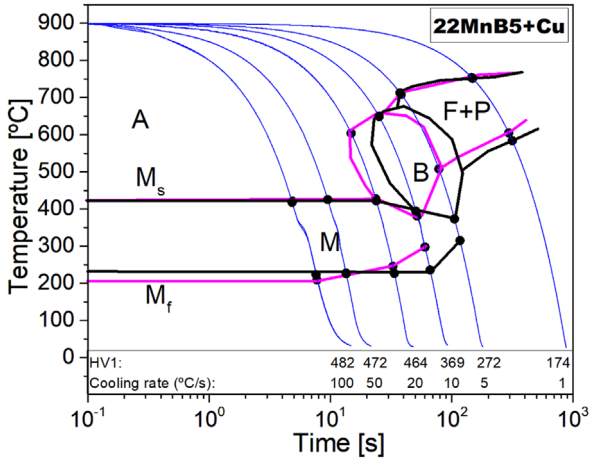
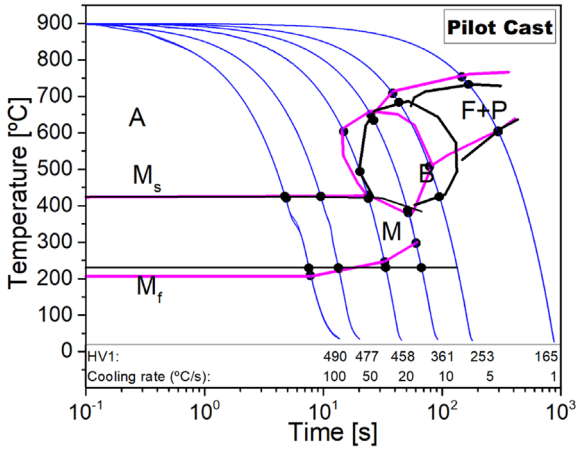


(c)

Fig. 3. CCT Curves generated from the experimental casts with different contamination profiles; CCT of the "Base" composition is superimposed in red for clarity. *a*) Mo+ Cast (0.1% Mo, +0.1 above the Base composition); *b*) Cr+ Cast (0.51% Cr; +0.20 above the Base); *c*) Cu+ Cast (0.39% Cu, 0.3 above Base).

Table 4. Composition (wt%) of the resulting steel.

C	Si	Mn	Cr	Al	Cu	B
0.23	0.18	1.16	0.29	0.04	0.08	0.003



(a)

Fig. 4. CCT Curve corresponding to the Industrial Cast; CCT of the "Base" composition is superimposed in red for clarity.

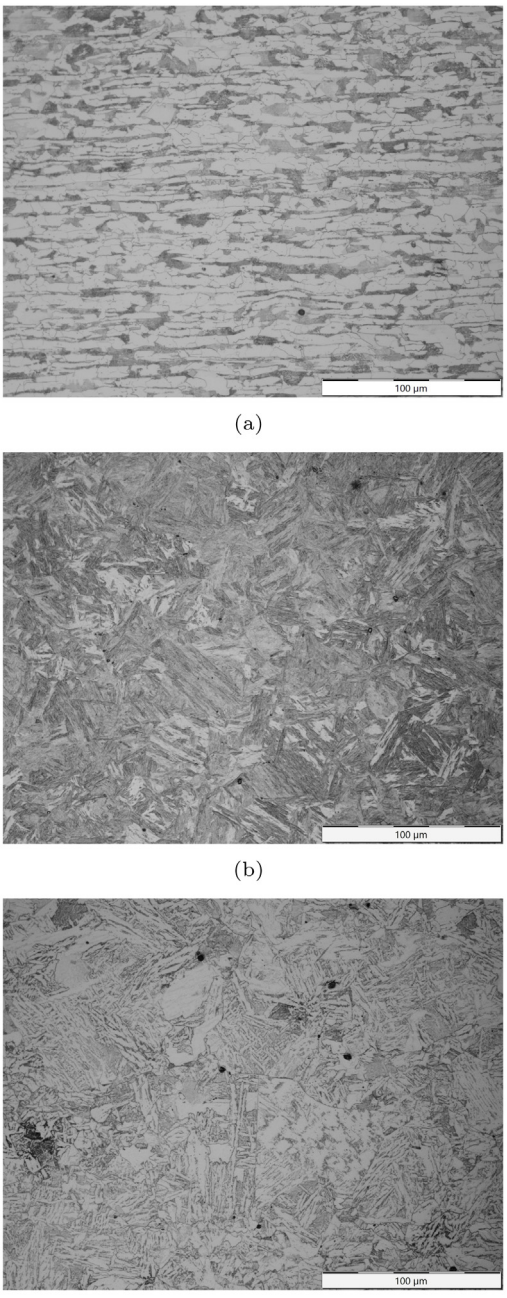
3.3 Pilot cast

A cast was produced in an industrial Electric Arc Furnace installation, using available scrap and correcting the chemical composition trough ferroalloys. This 160 t cast was produced using a mixture of scrap mainly coming from the studied packages sorts, in an approximate proportion of 5% *Pre-Consumer A*, 55% *Pre-Consumer B* and 8% *Post-Consumer*, with the rest ore-based metallic additions (e.g. master alloys, DRI).

Steel was continuous cast in a round format, and hot rolled into a 4 mm thick flat band. This material was supplied in an annealed state with no surface treatment. Chemical composition of this steel (Tab. 4) shows values in line with the expected in a 22MnB5 grade. Notably, all residuals are kept in very low levels: Cr at 0.3% is in line with the expected composition, Mo is kept under the detection limit of the OES equipment used (<0.03%) and Cu at 0.08%, inside the usually accepted range for sheet metal [11].

It is worth noticing that this Cu level is in line with mixing in the described proportions *Pre-Consumer* scrap with an approximate 0.08% Cu, *Post-Consumer* scrap with 0.3% Cu and DRI and metal additions with 0% Cu, in line with the estimations in [11].

As previously done with laboratory casts, a CCT study was performed for this pilot production. Results are shown in Figure 4, superimposed to the *Base* laboratory cast. In this case, differences are slight, with the Bainitic nose showing some distortion but no significant displacement.



(a)

(b)

(c)

Fig. 5. Micostructure corresponding to the different heat treatment conditions: *a*) As Produced; *b*) Full Quench; *c*) Soft Zone.

The material thus produced was cut into samples, and different heat treatments usual for hot stamped material were applied. As the steel was available in thick strip, parameters were based on the studies of work [17], where 6 mm sheet was used. Obtained microstructures are shown in Figure 5. Tensile tests were performed on these heat treated samples. Results are summarized in Table 5, along with some reference values found in the literature.

Table 5. Mechanical properties of the recycled 22MnB5 grade produced. Literature references, noted by an * symbol, have been added for comparison; please note that thickness is not constant across references.

State	Austenitization	Quench	Hardness [HV1]	Rp [MPa]	Rm [MPa]	E [%]
As Produced	n.a.	n.a.	178 ± 4	446 ± 2	611 ± 5	25.5 ± 0.8
Full Quench	600 s @930 °C	Water-Cooled Die	464 ± 9	1198 ± 12	1426 ± 11	2.9 ± 0.8
Soft Zone	600 s @930 °C	200 °C Die	243 ± 4	1076 ± 35	1171 ± 38	1.5 ± 0.07
As Produced* [13]	–	–	–	457	608	–
As Produced* [17]	–	–	–	404	596	14.2
Full Quench* [13]	–	–	–	1010	1478	–
Full Quench* [17]	600 s @930 °C	Water-Cooled Die	–	1160	1523	4.8
Soft Zone* [17]	600 s @930 °C	200 °C Die	–	533	796	8.2

The microstructure was studied in the initial state. Results, a Ferrite-Pearlite banded structure, were in line with the commonly expected in sheet 22MnB5. As-Produced material shows Hardness (178 HV1), Yield Strength Rp (446 MPa) and Ultimate Tensile Strength Rm (611 MPa) also in line with Ferrite-Pearlite Boron steel, as is the measured elongation (25%).

Martensitic microstructures were produced by austenitizing steel and quenching in a water-cooled die mounted in a hydraulic press; these samples have been identified as *Full Quench*. Austenitization was performed at a furnace temperature of 930 °C, keeping the samples for a total of 600 s including heating and soaking time. The quench was performed in a flat die kept at 16 °C by water cooling channels. Samples were manually transferred from the furnace to the die, with total air time in the 5–10 s range: due to the thickness of the material, samples reached the die at a temperature above 800 °C. Die was closed under a contact pressure of approximately 20 MPa, and kept closed for 30 s to ensure that samples had reached room temperature. As austenitization was performed in open (oxygen-containing) atmosphere, all samples showed significant scaling. The obtained microstructure (Fig. 5b) corresponds predominantly to Martensite, with possible inclusion of lower Bainite phases. Overall, the observed structures are equivalent to a hot stamped thick boron sheet. *Full Quench* material shows properties also in line with a Martensitic boron steel. Hardness (464 HV1) and strength (Rm 1426 MPa) reach values corresponding to a successfully quenched 22MnB5 [13]. Elongation values, in the 3% range, are acceptable, but low in comparison with the industrially expected 4–5%.

A *Soft Zone* condition was created by using a heated tool for the quench. Austenitization was performed in the same conditions as in martensitic samples. In this case, however, quenching was performed in a set of flat dies heated at 200 °C. Dies were manually closed, and samples were extracted after 30 s, being finally allowed to air cool into room temperature. Again, this treatment replicates the conditions used in work [17]. In this case, the microstructure (Fig. 5c) shows a Bainite-Martensite mixture. This *Soft Zone* condition fails to reach the expected values close to Rm 800 MPa, reaching almost 1200 MPa. One of the possible reasons is that the conditions used in [17] were suited for a high thickness material (6.2 mm in the cited work), resulting in excessive cooling for the 4 mm sheet. However, another consideration is the enhanced quenchability hardenability of this recycled material when compared to pure 22MnB5, that could lead to higher Martensite fraction. This can be seen in the compared CCTs in Figure 4: for instance, cooling paths in the 10-5 K/s would result in formation of some ferrite in the pure 22MnB5 composition, but avoid this transformation for the studied pilot cast. Unfortunately, it was not possible to quantitatively compare microstructures between this work and the literature reference, while the microstructures look similar from a qualitative point of view.

4 Conclusions

This work has explored the overall feasibility of using the EAF route to produce scrap-intensive high performance steel, namely Boron steel for press hardening applications. This study has been centered around the metallurgical aspects, particularly the effect on transformation curves and its implications on the process. The following conclusions could be drawn:

- Forming and processing scrap shows relatively low alloying levels, resulting in a good base for most automotive alloys. Most potential residual elements are kept at very low content. Exceptions to this, including high Mn or Cr fragments, point to potential improvements in scrap management, as their detection and separation would allow reclaiming these valuable elements for high alloy steel recycling.
- Post-consumer scrap is laced with nonmetallic inclusions, as well as unwanted metals most relevantly Copper. This Copper, present as wires tangled into the scrap, is enough to reach 0.2–0.3% in weight, in line with predictions in the available literature.
- The effect of Cr, Mo and Cu as residual elements was studied, showing in all cases significant displacement of CCT curves and increased quenchability hardenability even at moderate levels of contamination.
- Boron steel sheet for hot stamping appears to be a valid use case for steel recycling, as the CCT displacement caused by the most common residual elements translates into a mild improvement in material processability, while

avoiding possible problems associated with cold forming. However, in the case that soft zones via tailored cooling routes are desired the level of residuals needs to be carefully monitored, as intermediate quench conditions can interact with the displaced CCTs in unexpected manners.
– From the point of view of phase transformations, introduction of scrap-heavy products in the market needs to account for residuals and their effect of hardenability, particularly in cases where microstructral tailoring is involved.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

No data are associated with this article.

Author contribution statement

Conceptualization, J.P.; Methodology-laboratory tests J.P., E. G., M.G. and A.B.; Methodology-pilot cast F.E.; Software, X.X.; Validation, J.P, E.G. and M.G.; Formal Analysis, J.P. and A.B.; Investigation, J.P.; Resources, J.P. and F.E.; Data Curation, A. B.; Writing – Original Draft Preparation, J.P; Writing – Review and Editing, E.G., M.G., A.B. and F.E.; Visualization, J.P. and A.B.; Supervision, J.P.; Project Administration, J.P. and F.E.; Funding Acquisition, J.P. and F.E.

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