Original Article

Development of Cr-alloyed high carbon sheet steel – BW AC C77MD – for the manufacture of clutch bearing rings by deep drawing

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Abstract

Clutch bearing rings are high-performance parts that require excellent cleanliness and microstructure homogeneity to meet their wear and fatigue requirements. To improve productivity and reduce costs, a modified Cr alloyed steel with high carbon content has been developed by bearing manufacturers in cooperation with steel producers, which is well suited in terms of formability and is widely used in the production of automotive components, where it is purchased in the form of the cold-rolled strip for forming. This work investigated the process parameters and critical characteristics for developing Cr-alloyed sheet steel with high carbon content to produce clutch bearing rings on an industrial scale. Tensile test, hardness test, optical microscopy (OM), and scanning electron microscopy (SEM) were used to evaluate the mechanical and metallurgical properties of the studied steel throughout the process (casting, hot rolling, cold rolling + batch annealing, and heat treatment). The results have shown that it is possible to tune the mechanical properties of high-carbon steel at each stage of the process by using the proper heat and metallurgical treatment targeted at the requirements of the final application.

Keywords: High carbon sheet steel; C77MD; Clutch bearing ring; Deep drawing.

1 Introduction

Clutches are used to decouple the transmission system from the engine when starting from a standstill and when gear changes are necessary. The gradual increase in torque transmission from engine to the transmission must be smooth. Once the vehicle is in motion, the disconnection and pickup of the drive for gear selection must occur quickly and without fierceness, snatch, or shock [1].

One of the most critical parts of the clutch is the bearing that sits on the release lever and holds the crankshaft and the diaphragm. To produce components with high mechanical strength that make up a bearing, such as rings (Figure 1a, f) and rolling elements (Figure 1c), steels with high carbon content and high microscopic cleanliness which, after appropriate mechanical processing, undergo quenching and tempering heat treatment, for are traditionally used. Steels with low carbon content are also frequently used for bearing ring production, depending on the application conditions. These lower carbon steel, however, must undergo surface hardening, such as carburizing and subsequent quenching and tempering, to meet wear resistance requirements [2].

On the other hand, the cold forming of high-carbon steels is increasingly critical due to their relatively high mechanical strength compared to low-carbon steels, even if the supplied raw material is supplied with a spheroidized microstructure, which is fundamental for cold forming of high-carbon steels.

In 1993, Andersson-Drugge and Lund [3] presented a steel with a eutectoid composition that exhibited good as-rolled forming properties due to microstructural aspects resulting from a controlled process and limited addition of alloying elements. To improve operations and achieve economic benefits in the final cost of the product, steel

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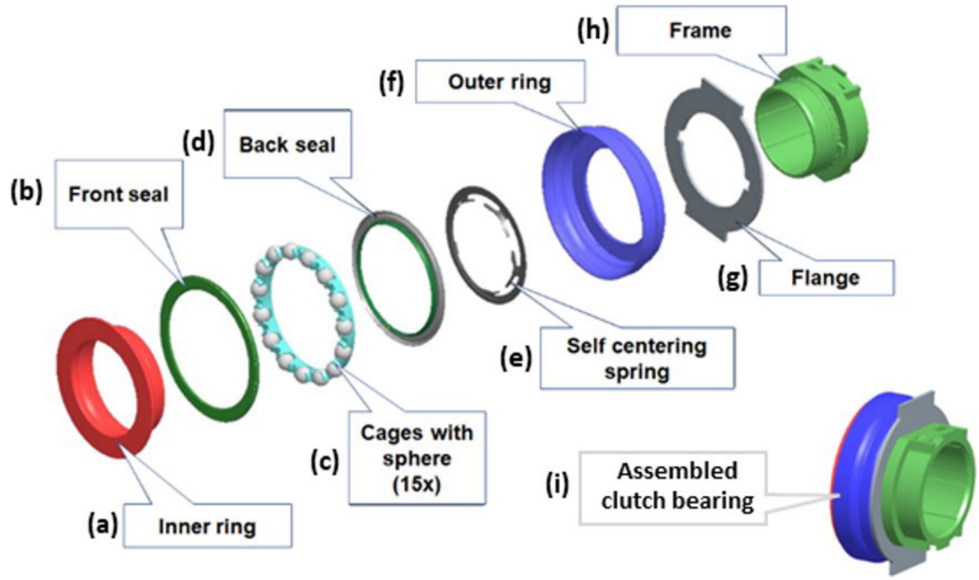


Figure 1. An exploded view of the clutch bearing shows: (a) inner ring; (b) front seal; (c) cage with spheres; (d) back seal; (e) self-centering spring; (f) outer ring; (g) flange; and (h) frame. (Provided by Schaeffler).

mills, re-rollers, and automotive component manufacturers are working together to improve processes and supply the raw material for components in an optimum condition for forming.

In this context, modified C80U steel, developed by bearing manufacturers in cooperation with steel producers, is well suited in formability and is widely used in the production of automotive components, starting from a cold-rolled strip for forming. Stamping processes in progressive presses have the significant advantage of high productivity compared to traditional machining bearing rings.

The modified C80U steel corresponds to a variant of C80U steel according to EN ISO 4957 [4], with a chromium addition of about 0.5%wt, which gives the steel a higher hardenability, an essential metallurgical property in the subsequent heat treatment by quenching and tempering. This gives the final product the high mechanical strength required for the application. Chromium, present in virtually all bearing steel alloys, not only increases hardenability but is also a strong carbide former contributing to wear resistance [5].

The typical microstructure of a quenched and tempered high-carbon steel consists of a martensitic matrix with primary carbides (which are not dissolved during austenitizing) [6]. The hardness along the cross-section of a hardened bearing steel usually is 60 to 64 HRC (697-800 HV) [7]. In addition to a satisfactory microstructure achieved by a combination of chemical composition and heat treatment, another fundamental characteristic of bearing steel is its microscopic cleanliness, i.e. a low percentage of nonmetallic inclusions. This is a fundamental requirement for bearing durability in the face of cyclic loads that lead to fatigue fractures [2].

Table 1. Chemical composition BW AC C77MD

C (wt.%)	Mn (wt.%)	Cr (wt.%)	Total O (wt.%)	P (wt.%)	S (wt.%)
0.72-0.82	0.20-0.70	0.40-0.60	≤0.0030	≤0.020	≤0.006

2 Material and methods

2.1 Material

The BW AC C77MD steel was developed based on the Modified C80U chemical composition to fit clutch bearing ring application. The objective of the development was to reach excellent formability and hardenability as cold rolled, as well as high hardness and wear resistance post quenching and tempering. Due to its high alloying content (C and Cr), shown in Table 1, its production is very complex in every process step.

The steel was produced as hot rolled coils (HRC) at ArcelorMittal Tubarão (Steelmaking / Continuous casting / Slow cooling / Slab reheating / Hot rolling / Packing), transformed to cold rolled coils (CRC) at Waelzholz Brasmetal Laminação (Pickling / Longitudinal cut / Cold rolling / Batch annealing / Skin pass / Packing) and shaped into the clutch bearing ring at Schaeffler Brasil (Blank cutting / Deep drawing / Austenitization + Quenching / Tempering). To achieve the performance needed for the clutch bearing ring, this steel is produced through a specific steelmaking route (Figure 2) to ensure a low content of non-metallic inclusions to meet the client's specifications.

Figure 3 summarizes the thermomechanical process applied to the studied steel, also pointing out which stages total characterization samples were taken (HRC, CRC, and part) in the present work.

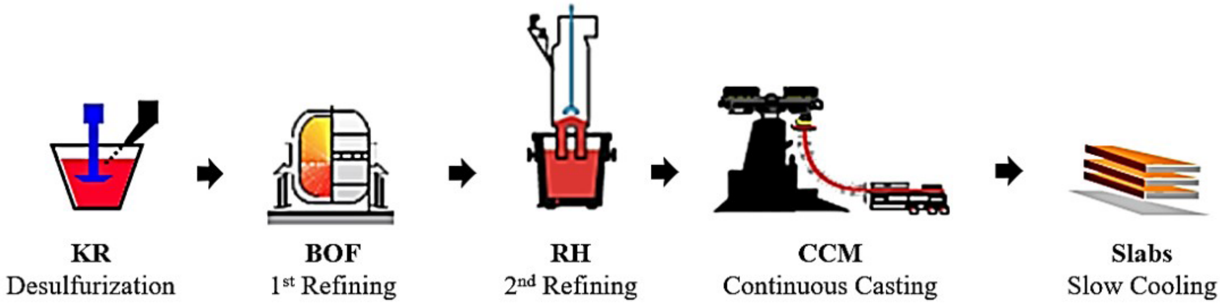


Figure 2. Slab production stream at ArcelorMittal Tubarão to guarantee low inclusion levels.

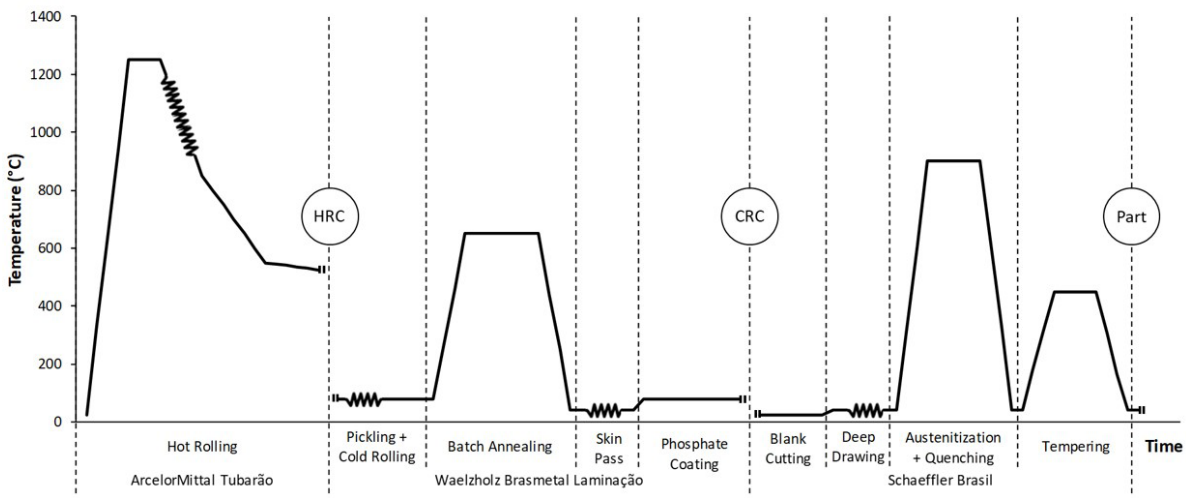


Figure 3. BW AC C77MD steel thermomechanical process stream for clutch bearing ring production.

2.2 Methods

Slab samples (transversal and longitudinal) were gas cut, had their surface leveled by milling, and sanded using a swinging sander. The samples were then etched with an ammonium persulfate solution (25%) for 10 seconds, washed with water, and dried with forced air. The sample's surface was then inspected and documented.

HRC, CRC, (both taken from the middle of the length, longitudinal direction) and part samples (flat part of the rings, longitudinal) were prepared for microstructural analysis as follows: cutting, mounting in resin, sanding (silicon carbide from 100 to 1200 mesh, using water), and polishing (3μm and 1μm diamond paste). To analyze microstructure morphology, the samples were etched by immersion using Nital 2% for 30 seconds or until the surface was darksome [8], whereas, to analyze internal cleanliness (inclusion level) and intergranular oxidation depth, no etchant was used to neither avoid masking nor accentuate oxidation depth perception. Two microscopes were used: Optical Microscope (OM), Leica DM6000 (light filed to evaluate inclusion level), according to EN 10247 [9] method K, and Scanning Electron Microscope (SEM), JEOL JSM7100F FEG (15kV, 8.2-10.6mm working distance, secondary electron detector).

Tensile tests were performed according to ABNT NBR ISO 6892-1 [10] (L_0 = 80mm) using a Zwick Z250 machine and contact strain gauge. Due to shape and size limitations of the part samples, Vickers microhardness tests were done along ¼ of the thickness of all samples, according to ABNT NBR NM ISO 6507-1 [11], using a Shimadzu HMV-G durometer.

3 Results and discussion

3.1 Steelmaking

The steel grade BW AC C77MD has the following requirements for steel refining:

- Need to desulfurize in the steel ladle after pouring from the LD with a long time of bubbling (over 10 minutes);
- Guarantee end-of-blow phosphorus below 100 ppm; therefore, blowing is also very demanding, with a high flux consumption (above 80 kg/t);
- Ensure that as little as possible converter slag enters the ladle during pouring to ensure desulfurization in the ladle and avoid phosphorus pickup;

- Need to desulfurize in the steel ladle after pouring from the LD converter and bubbling for a long time (over 10 minutes);
- Need to use graphite as a carbon addition due to sulfur restriction with high demand for addition control and better homogenization;
- Ensure a low oxygen level in liquid steel during casting, to avoid bubbles, porosities on casted slabs, and non-metallic inclusions in the steel.

The refining process begins at a KR (Kambara Reactor), Figure 3, where the pig iron is desulfurized as much as possible. Meanwhile, the scrap used for the converter process has been carefully selected to allow good control of residual elements. Primary refining in the converter is conducted to ensure low sulfur reversion during oxygen blowing. Additions, such as ferroalloys, especially graphite, are also selected to ensure low sulfur content. During tapping, it is important to guarantee as low as possible converter slag (< 3kg/t) enters the ladle when pouring to guarantee low S content and avoid phosphorus pickup. This is followed by secondary refining in the RH vacuum degasser to further control the O and S content and adjust the chemical composition.

The steel under study is cast on a curve mold continuous casting machine at ArcelorMittal Tubarão, the most recommended machine for casting high carbon steels with high alloy content due to its single bending point [12]. Special procedures were used to produce this steel, highlighting the strict control of the mechanical conditions of the casting machine (alignment and spacing between segments) and the rigorous control of the secondary cooling parameters. Another critical aspect of ensuring the steel's cleanliness was optimizing the heat sequence in the tundish to avoid material production at the beginning and end of a tundish sequence.

Samples were taken from the third slab cast in each strand to evaluate the internal quality results (center line segregation and cracking) by macro etching (Figure 4). No longitudinal, transverse, lateral, or corner cracks (Figures 4a, b, c) were detected. Normal centerline segregation (Figure 4d) was found, typical for the continuous casting process, especially for steels with high carbon and alloy content.

To ensure low inclusions, specific tundish cover materials were used to allow better absorption of these inclusions and fine-tuning of the argon injection and sealing process of the valves during continuous casting of the heats. In addition, other high carbon steel grades with lesser cleanliness requirements are produced in the same tundish before this grade to optimize overall process yield. After casting, the slabs were cooled slowly in pits for four days to ensure thermal contraction and phase changes did not cause cracking. This step is essential because of the high hardenability of the material.

Steel cleanliness is a feature in the steel shop, but the EN 10247 method K (average of fields) evaluation is performed on HRC samples. The results show no inclusions classified as K3 or higher. The average value for K2 was 0.439, while the average value for K1 was slightly higher at 2.488 inclusions/mm^2 (Figure 5).

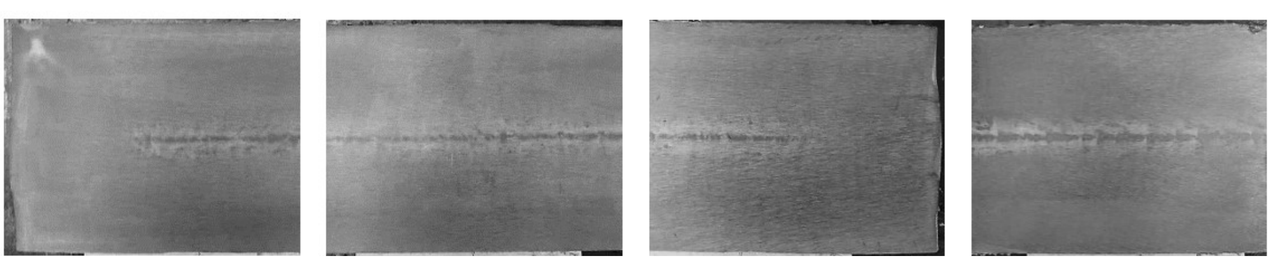
No value was found above the requirement for applying clutch bearing rings (K1 $\leq$ 10). Ensuring a high degree of cleanliness, i.e., a low percentage of nonmetallic inclusions, is paramount to ensure bearing durability against fatigue fractures.

3.2 Hot rolling

After casting, the slabs were charged into the reheating furnace of the Hot Strip Mill (HSM). Since BW AC C77MD has a higher carbon content than the similar high carbon steels hot rolled at ArcelorMittal Tubarão, a more cautious approach was used for the HSM setup (e.g., higher thickness, crown, and temperatures). When the mathematical model converges and the process stabilizes, the setup is gradually changed to improve temperature, rolling speed, and crown values to avoid shape defects such as coil sagging and wedge formation and achieve the desired microstructure (HRC). Nominal HRC thicknesses of 2.65 to 5.50 mm were achieved after the stabilization of the hot rolling process.

To obtain a suitable cross-section thickness profile for the following process, cold rolling (Figure 3), it is necessary to aim for low crown values and to restrict the scheduling conditions to produce it with low roll wear conditions in the roughing and finishing mill.

Because of its high hardenability, it is essential to ensure that no brittle phases (e.g., martensite) form during hot rolling, cooling on the run-out table (ROT), and coiling. This could cause the material to shatter, producing brittle splinters that pose a safety risk. Therefore, as a safety measure, evacuation of the areas adjacent to the HSM is mandatory



(a) (b) (c) (d)

Figure 4. BW AC C77MD representative macro etching photographs, transversal (a) left side, (b) right side, (c) middle, and (d) longitudinal.

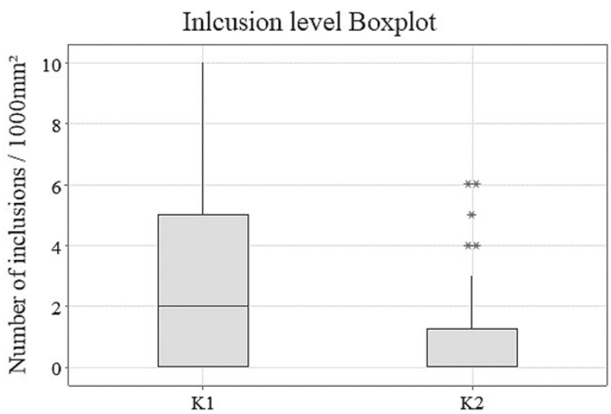


Figure 5. Inclusion level Boxplot for HRC samples.

during the rolling of high-carbon steels at ArcelorMittal Tubarão. In addition, the hot rolling process (Figure 3) is subject to rigorous control of the finish delivery temperature (FDT), the coiling temperatures (CT), the rolling speed, the cooling strategy, and the setting of the laminar flow model. To set these parameters, it is essential to know the time-temperature-transformation (TTT) diagrams of the steel to find the optimal combination of parameters to avoid brittle microstructure and intergranular oxidation on the surface of the strip. Ferreira [13,14] took the same precautions to successfully produce other high carbon grades at ArcelorMittal Tubarão for chainsaw chain and diaphragm spring application.

Micrographic analysis of HRC samples has shown a fully pearlitic microstructure (Figure 6). Lopes [15] conducted similar industrial trials with high carbon and lower Cr alloy grades, resulting in a mainly fine and homogeneous pearlite microstructure.

Grain boundary oxidation on the steel surface could lead to cracks or fissures along the steel surface and hence to premature fatigue. As shown by Ronqueti's research [16], coiling temperatures should be as low as possible, below 600°C, to reduce grain boundary oxidation. Therefore, combined with the high hardenability of BW AC C77MD, coiling temperature/coil cooling becomes one of the significant challenges of the hot rolling process with a very narrow working window to achieve a suitable microstructure and low grain boundary oxidation. No grain boundary oxidation was observed at the most sensitive region of the HRC (Figure 7), mid-length and mid-width, even though an oxidation depth of 5 µm is tolerable at this location.

3.3 Cold rolling and batch annealing

HRC was pickled continuously, in which the coil was immersed in a heated hydrochloric acid solution, followed by water rinsing, neutralization, drying, and oiling of the surface to remove surface oxides formed during hot rolling. Then, the coil is cut in a shear-slitting process with rotating knives to obtain coils compatible with the widths of the subsequent stages.

The cold rolling process is carried out in a four-high reversible cold rolling mill equipped with an automatic thickness control system that ensures compliance with stringent tolerances along the entire length of the strip. The sensitive and precise system for regulating the rolling force, combined with thickness control by X-ray diffraction, can correct most thickness variations caused by hot rolling. The resulting CRC nominal thicknesses were between 1.60 and 4.00mm.

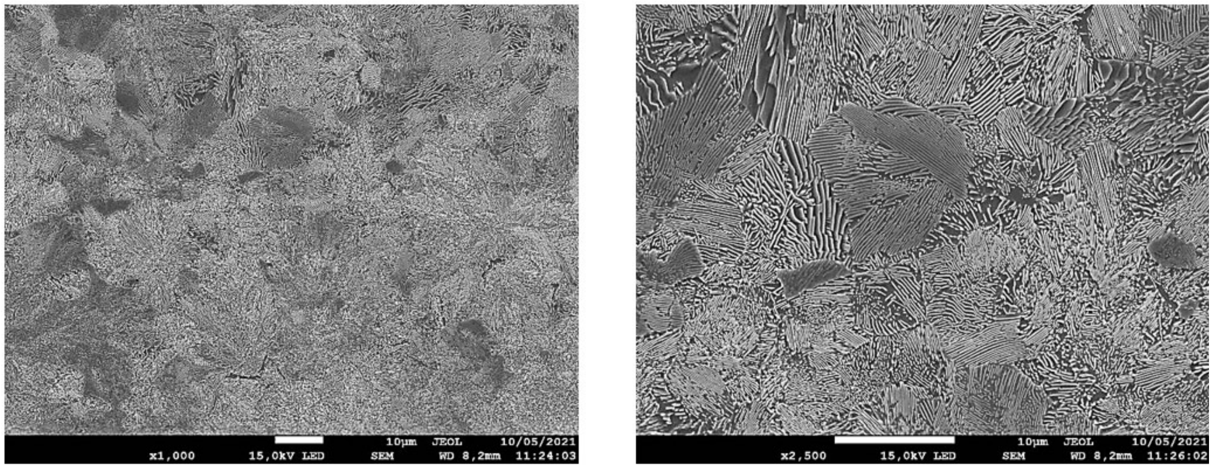
Subcritical batch annealing heat treatment is carried out in high convection annealing furnaces operated with hydrogen (H_2) inert gas and with uniform temperature distribution to achieve high surface quality, homogeneous mechanical properties, and uniformly distributed spheroidal carbides in a ferritic matrix microstructure. The temperature gradient, heating time, and cooling rate are controlled to ensure uniformity of microstructure and mechanical properties. After annealing, the material is skin passed to determine the final thickness, crown profile, surface finish (appearance and roughness), and mechanical properties and to provide shape stability.

CRC specimens exhibited a homogeneous microstructure consisting of a ferrite matrix and scattered carbides (Figure 8), cementite, and Cr-enriched carbides. In addition to their importance in the forming process, spheroidal carbides provide an optimum initial microstructure before quenching heat treatment, which means a lower tendency to austenitic grain growth, an extension of the permissible range of quenching temperatures, a lower tendency to crack during quenching, and higher strength and toughness of the quenched and tempered steel [17].

As expected, the two very different microstructures observed in the specimens from HRC (Figure 7) and CRC (Figure 9) led to very different results in the tensile tests (Table 2). It is easy to see that the yield stress (YS) and tensile stress (TS) decrease by about 50%, and the elongation (El50) increase by 150%.

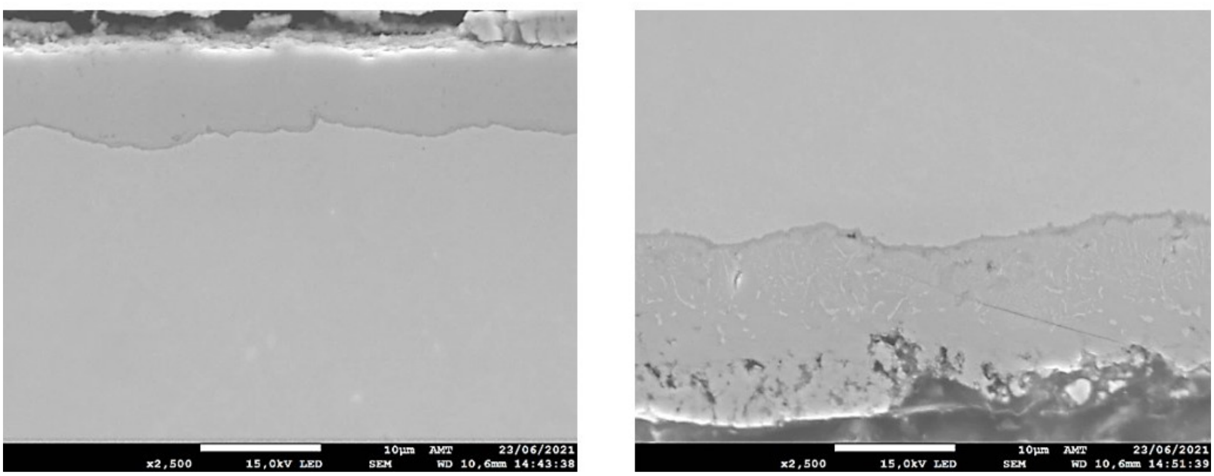
To make sure BW AC C77MD steel will be fit for the deep drawing process, a zinc phosphate coating is added to the surface to reduce friction and, consequently, tool wear significantly during forming operations, making complex multistage forming processes involving more rigid materials possible.

Phosphating is a continuous process composed of the following steps: pretreatment to clean the surface; refiner to condition the surface; zinc phosphate bath, where nucleation and growth of zinc phosphate crystals take place (2.0 to 6.0 g/m^2) (Figure 9); neutralizer to neutralize and passivate the surface; post-treatment in a bath of reactive soap to form layers of sodium (0.50 g/m^2 maximum) and zinc stearate (0.20 g/m^2 minimum), which also helps in the drawing processes; water rinses during the intermediate steps between the different stages. The concentrations and pH values of the baths are controlled during the process.



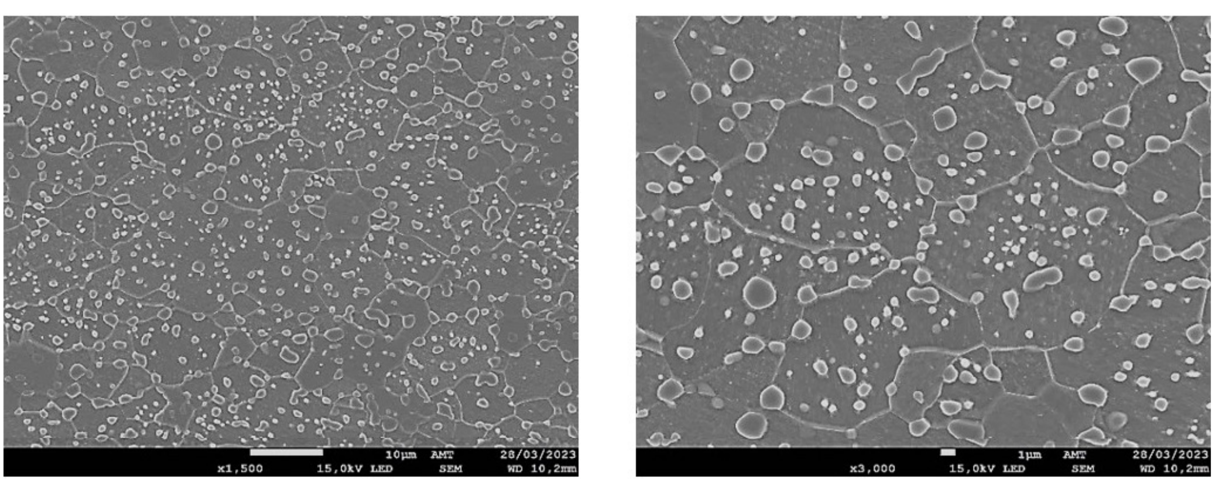
(a) (b)

Figure 6. Micrographs of Hot Rolled sample, (a) 1000x and (b) 2500x. SEM – SE – Nital 2%.



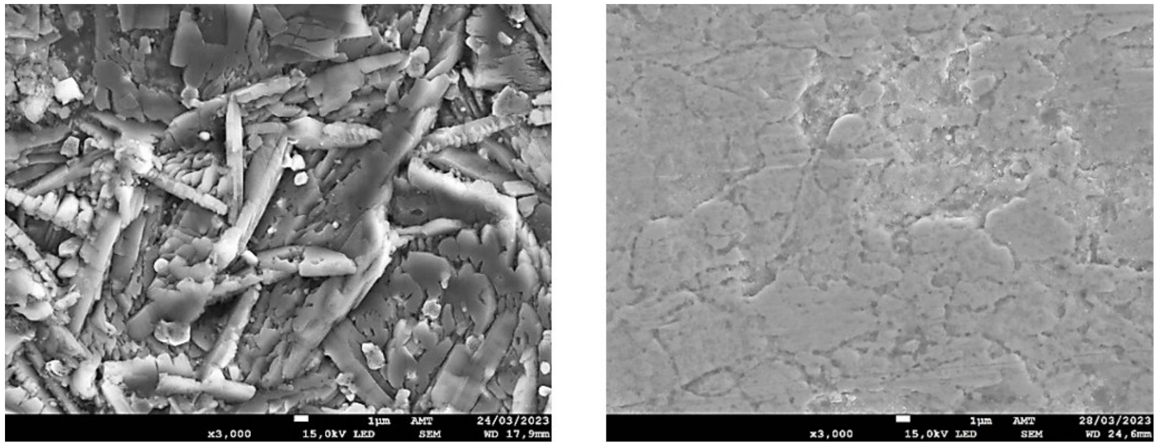
(a) (b)

Figure 7. Micrographs of Hot Rolled sample near the surface, 2500x, (a) Topside and (b) Bottom side. SEM – SE – No etchant.



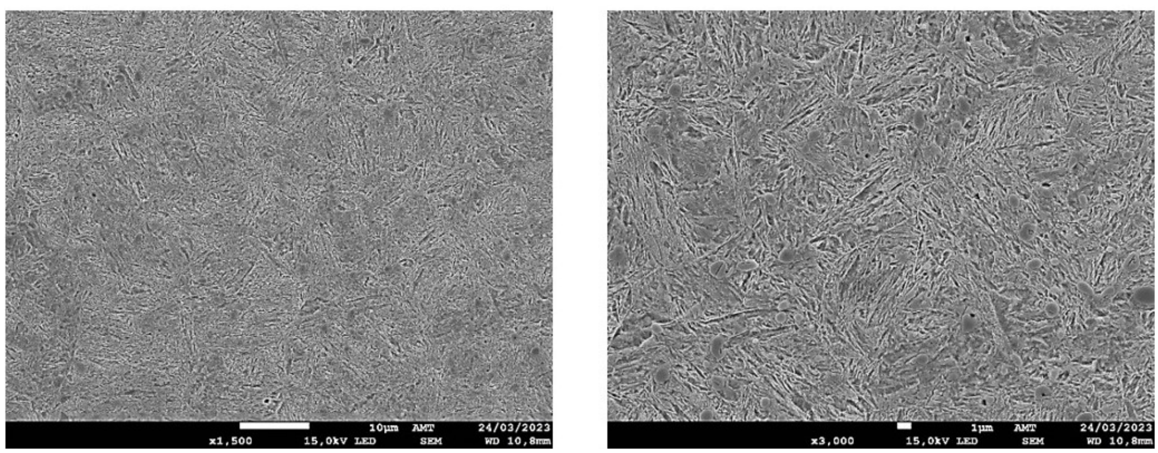
(a) (b)

Figure 8. Micrographs of Cold Rolled sample, (a) 1500x and (b) 3000x. SEM – SE – Nital 2%.



(a) **(b)**

Figure 9. Micrographs of cold-rolled sample surfaces (a) with and (b) without zinc phosphate coating. 3000x. SEM – SE – No etchant.



(a) **(b)**

Figure 10. Micrographs of Clutch bearing ring sample after Quenching and Tempering, (a) 1500x and (b) 3000x. SEM – SE – Nital 2%.

3.4 Clutch bearing ring production

CRC is delivered in the phosphatized state and undergoes a multi-stage sequential drawing process to achieve the part's final shape. The part is then quenched and tempered to achieve metallurgical and mechanical properties suitable for use as a bearing ring. This is followed by grinding and calibration of the dimensions.

Part samples have a microstructure consisting of a fine martensite matrix associated with scattered primary carbides, which are not dissolved during austenitization (Figure 10). They originated from the spheroidized microstructure before heat treatment (CRC). Martins et al. [18] found the same microstructure with similar steel.

Vickers microhardness measurements were performed along ¼ of the thickness of all specimens (Figure 11).

The mean results of the HRC (313 HV) and CRC (184.5 HV) specimens confirm the results of the tensile tests (Table 2) and the observed microstructure, i.e., fully pearlite and ferrite + coarse scattered carbides. Q+T Part specimens showed a mean result (713 HV) higher than the HRC value, which is within the expected values of 697-800 HV (60-64 HRC) [6] from the

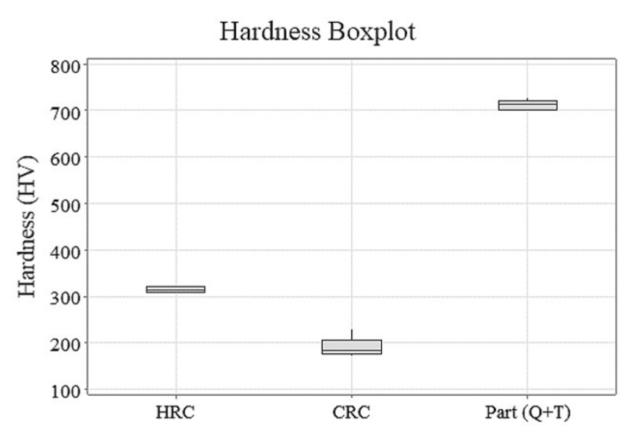


Figure 11. Hardness Boxplot for BW AC C77MD tested samples.

Table 2. Tensile test results BW AC C77MD

Sample	Direction	YS (MPa)	TS (MPa)	El80 (%)
HRC	0°	645	1042	8.9
	90°	721	993	10.8
CRC	0°	340	500	26.8
	90°	351	507	23.6

literature and like the results found by Martins (760HV) [18]. CRC Results showed a greater spread than HRC and Q+T Part samples, probably related to the greater sensitivity of the Vickers microhardness method and the presence of two very different microstructural constituents: Ferrite and Carbides.

As explained in this article, manufacturing clutch bearing rings with BW AC C77MD is complex and requires careful attention to crucial details.

4 Conclusions

- Strict control of steel refining and casting parameters is essential to ensure the remarkably high degree of cleanliness required for clutch bearing rings.
- The working window of the hot rolling process is very narrow to achieve a fully pearlitic microstructure and prevent grain boundary oxidation at the surface.
- The spheroidization treatment and phosphating at the Re-roller are essential features to enable the production of bearing rings by deep drawing.
- Microstructure control is imperative throughout the process to improve the performance of the steel both in the downstream process and in the final application.
- BW AC C77MD meets critical metallurgical properties and quality requirements to produce clutch bearing rings.

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