Original Article

Development of high-carbon low-alloy steel (BW BL 50CRMO4) at Arcelormittal Tubarão and Waelzholz Brasmetal rolling for final application in chainsaw bars

Henrique Severiano de Jesus [1*]
Fernando Generoso Neiva Ferreira [1]
Eduardo Alves Machado [1]
Fabiano Almir Barbosa [1]
Juliano Braz Possati [1]
Marcelo Urdapilleta Rodrigues [1]
Maurício Franco Bomfim [2]
Marina de Lima Barroso [2]
Daniel Augusto Ferro [2]
Thomas Frank [2]

Abstract

Over several decades, the industry has been constantly evolving in its manufacturing processes, with optimized and automated equipment ensuring greater stability. New alternatives are continually being proposed to reduce costs and improve competitiveness. This study presents the development of high-carbon low-alloy steel, BW BL 50CrMo4, at ArcelorMittal Tubarão and Brasmetal Waelzholz, as a re-rolled product to meet the demands of the chainsaw bar and tool market, providing a ready-to-use product and reducing the final customer's heat treatment steps. The production of this type of steel requires rigorous process control from the steel mill to re-rolling. These steels are widely used in components that require high mechanical strength, clarity, shape maintenance, and abrasion resistance. This study investigated, on an industrial scale, the process parameters and critical characteristics for developing a high-carbon steel sheet with Cr and Mo alloy for chainsaw bars. The steel was characterized throughout the entire process (casting, hot rolling, cold rolling + batch annealing, and heat treatment) using tensile testing, hardness testing, optical microscopy (OM), and scanning electron microscopy (SEM). The results showed the evolution of the material's microstructure, from a ferrite/pearlite microstructure in the hot band, spheroidized in cold rolling/annealing, to a fully bainitic microstructure after austempering, ready for the manufacture of chainsaw bars.

Keywords: High-carbon steel; chainsaw bar; ArcelorMittal Tubarão; Waelzholz Brasmetal Laminação.

1 Introduction

Chainsaws are mechanical cutting tools widely used in applications such as cutting wood or even ice. Typically powered by combustion engines, these tools are equipped with cutting elements attached to a structure known as a chainsaw guidebar (Figure 1). The guidebar is a component of the chainsaw cutting assembly and its main function is to support and guide the cutting chain. Due to the high mechanical demands on this part caused by the friction generated by the cutting chain, it requires strict performance, safety, and durability criteria.

Essential properties include mechanical strength and toughness to ensure the bar can withstand impact loads and tension without deformation. Toughness prevents catastrophic failures by absorbing energy, and dimensional stability ensures precision and consistency during use. The 50CrMo4 steel is a common choice for manufacturing chainsaw bars due to its superior properties. This steel offers high mechanical strength, good hardenability, while maintaining toughness, making it ideal for demanding applications.

This study thoroughly analyzes the production requirements, quality and specific properties of the 50CrMo4 steel and its importance in manufacturing efficient and durable chainsaw guidebars.

Steel 50CrMo4, according to theISO 683-2: 2016 [1], with 0.5% by weight of carbon and the addition of about 1.0% by weight of chromium and 0.20% by weight of molybdenum, gives the steel higher hardenability, an essential metallurgical property for subsequent heat treatment by

[1]*ArcelorMittal Tubarão, Serra, ES, Brasil.*
[2]*Waelzholz Brasmetal Laminação, Diadema, SP, Brasil.*

**Corresponding author: henrique.s.jesus@arcelormittal.com.br*

quenching and/or austempering, which imparts the high mechanical strength needed for the application to the final product. Figure 2 shows a CCT diagram for 50CrMo4 steel, demonstrating a particularly good hardenability window.

Chromium, which is present in almost all tool steel alloys together with molybdenum, not only increases hardenability but is also a strong carbide former, significantly contributing to wear resistance and high-temperature resistance [2].

The typical microstructure of an austempered high-carbon low-alloy steel consists of a bainitic matrix with primary carbides (which are not dissolved during austenitization) and with or without residual retained austenite. The hardness on the surface section of a hardened chainsaw guidebars steel is typically between 40 HRC (390HV) and 44 HRC (440HV). Additionally, to the adequate microstructure, another paramount characteristic of steel for chainsaw guidebars is its microscopic cleanliness, which must have a low-level of non-metallic inclusions. This is a crucial requirement for the durability of the guidebar under cyclic loads that lead to fatigue fractures [3].

2 Development

2.1 Material

The steel alloy 50CrMo4 – ISO 683-2 2016 [1] is a ferrous material classified as a special alloy steel. 50CrMo4 steel is specially developed for chainsaw guidebar application, featuring good formability and hardenability, and after austempering, high hardness and wear resistance. Due to its high alloying content (C, Cr, Mo), show in Table 1, its production is very complex in every step of the process.

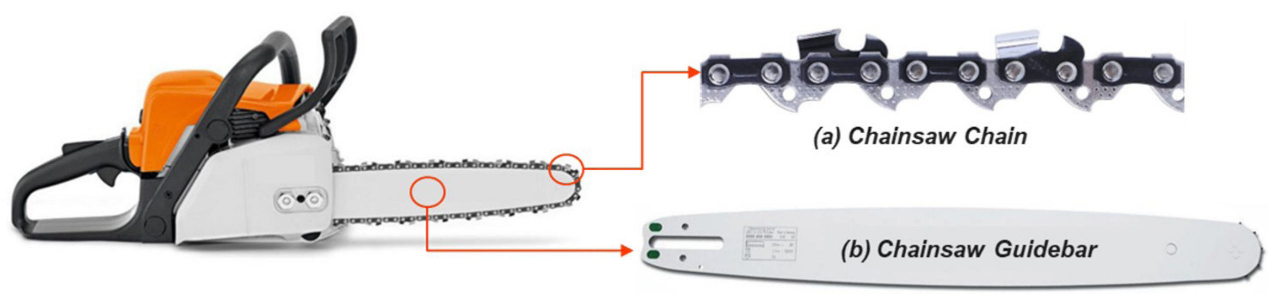


Figure 1. Chainsaws are composed of different steel parts, such as the chain (a) and the bar (b), which are the focus of the study.

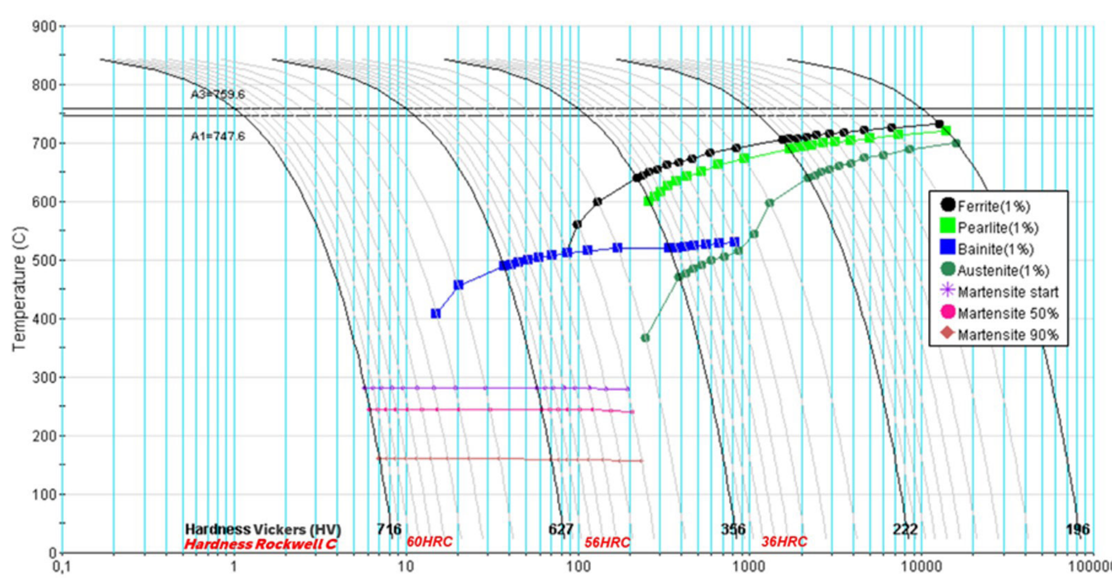


Figure 2. Continuous Cooling Transformation Diagram (CCT) BW BL 50CrMo4 by JMatPro V.13.

Table 1. Chemical composition of BW BL 50CrMo4 steel

C (%)	Mn (%)	Si (%)	Al (%)	Cr (%)	Mo (%)
0.50-0.56	0.55-0.75	0.15-0.40	0.020-0.040	1.00-1.20	0.20-0.30

The studied steel was produced as a hot-rolled coil (HRC) at ArcelorMittal Tubarão (Steelmaking / Continuous casting / Slow cooling / Slab reheating / Hot rolling / Packaging), Figure 3, and processed by Waelzholz Brasmetal Laminação (Pickling / Slitting / Cold rolling / Annealing / Austempering / Skin pass / Cutting / Packaging), Figure 4.

Figure 5 summarizes the thermomechanical process applied to the studied steel, also indicating the stages from which samples were taken for complete characterization both in hot and cold rolled coil (HRC and CRC, respectively).

2.2 Methods

2.2.1 Macro etching test

Slab samples (transverse and longitudinal) were prepared as follows: gas cutting, milling for surface leveling, and sand blasting using a pendulum sander. The samples were etched according to ASTM E340-2023 [4] with ammonium persulfate solution (25%) for 10 seconds, then washed with water and dried with compressed air, inspected, and photographed.

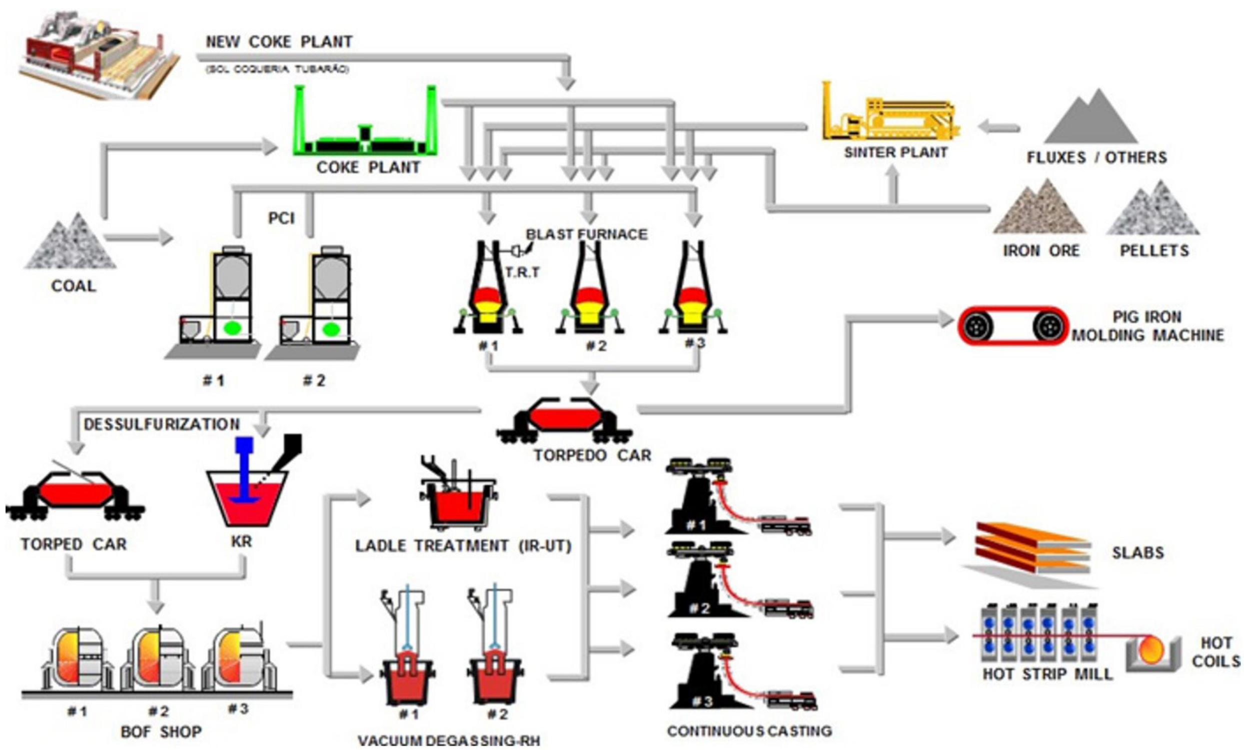


Figure 3. ArcelorMittal Tubarão production flowchart. #Alto-fornos na ArcelorMittal Tubarão.

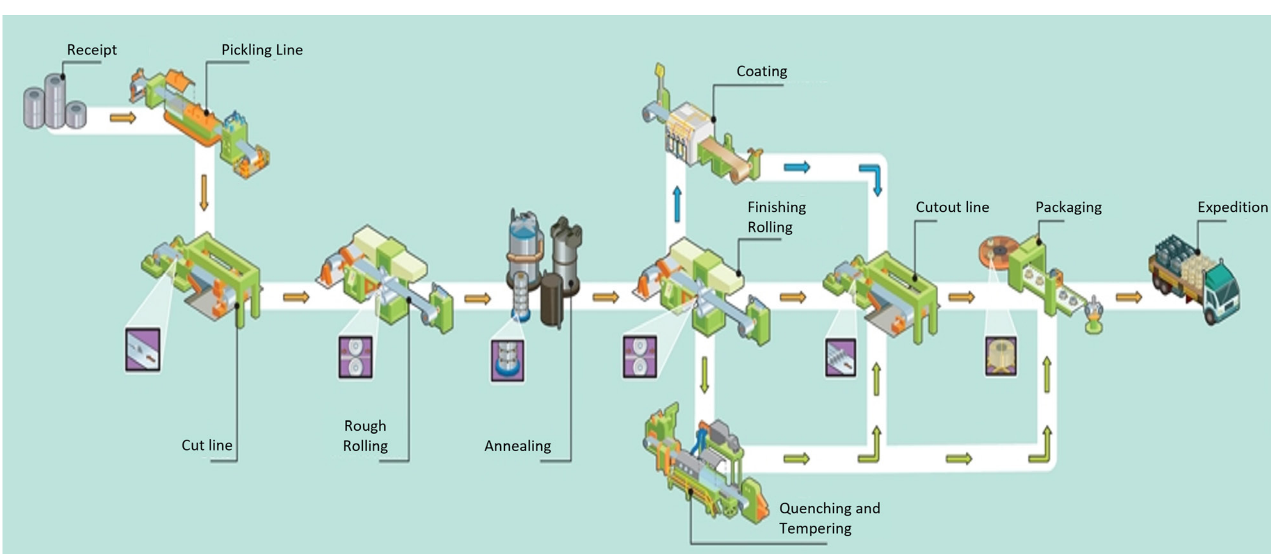


Figure 4. Production flowchart of BW BL 50CrMo4 steel at Waelzholz Brasmetal Laminação (main line without auxiliary processes).

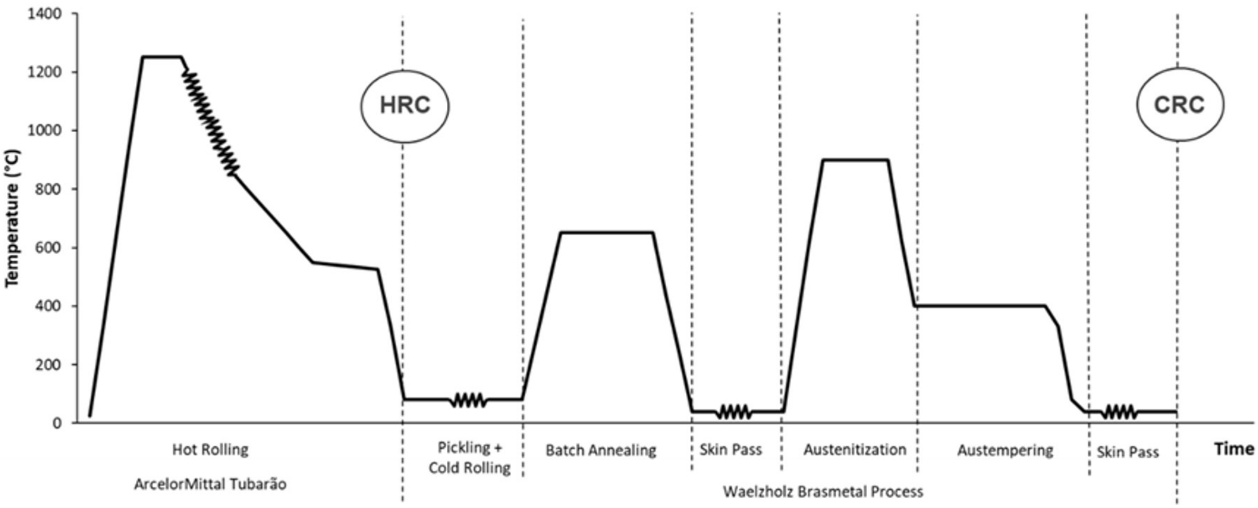


Figure 5. Thermomechanical process flow in BW BL 50CrMo4 steel until the final product.

2.2.2 Microstructural characterization

Both hot-rolled (HRC) and cold-rolled (CRC) coils, were traditionally prepared for microstructural characterization: cutting; hot mounting (Bakelite), grinding (silicon carbide paper: from 100 to 1200 mesh, successively, using water); manual polishing (3μm and 1μm diamond paste). For morphological analysis of the microstructure, the samples were etched according to ASTM E407-2023 [5] by immersion (2% Nital) for 30 seconds, or until the samples became matte, whereas for intergranular corrosion depth analysis, no chemical etching was used to avoid masking or increasing corrosion depth.

The samples were observed in a Scanning Electron Microscope (SEM), JEOL JSM7100F FEG (25kV, secondary electron detector for morphology and backscattered electrons for analysis of the microstructure present in HRC and CRC after austempering, as well as evaluation of intergranular corrosion, 10 mm working distance).

EBSD analysis was conducted to evaluate properties not commonly observed in conventional analyses on the CRC sample after austempering. For this, conventional preparation was followed by 18-hour polishing on a vibratory polisher with Buehler MasterMet 2 colloidal silica. In the SEM analysis, the parameters used were: tilt 70°, magnification of 500x and 1000x at 1/4 of the thickness, WD of 20mm, voltage of 20kV, mode 4x4, exposure time 165, and step size of 0.3 microns.

2.3 Mechanical characterization

Three specimens (Lo=50 mm) were extracted from the HRC and CRC in the longitudinal direction by treatment condition, and the tests were conducted according to ABNT NBR ISO 6892-1 [6] on a ZWICK Z250 machine, with a contact extensometer (strain-gauge). Rockwell C hardness tests were also performed on the CRC samples after heat treatment. The CRC samples were tested on a ZWICK ZHU 250 hardness tester, model CL-A, according to ABNT NBR NM ISO 6507-1 [7].

3 Results and discussion

3.1 Steelmaking

The BW BL 50CrMo4 steel presents the following challenges for its refining:

- Keep sulfur content below 30 ppm in Si-Killed steels without using desulfurization in the secondary refining station.
- Keep aluminum content below 0.025% in the RH Vacuum Degasser, even with chemical heating.
- Reduce the level of oxygen in the liquid steel during casting to avoid bubbles and porosities in the slabs and even cause breakout during casting; and ensure a high level of cleanliness in the liquid steel.

The steel manufacturing process starts at the Kambara Reactor (KR), where pig iron is desulfurized to a maximum of 10 ppm of sulfur. The scrap used is rigorously selected, and refining in the converter ensures low sulfur reversion during oxygen blowing. Ferroalloy additions, mainly recarburizers, were specially made to maintain the low sulfur content. During thermal heating, the aluminum content is controlled as to not exceed the allowed limit. After this step, desulfurization of the liquid steel occurs in the converter. In the RH Vacuum Degasser treatment, chemical heating with FeSi occurs first. Three experimental heats were cast using ArcelorMittal Tubarão

Figure 6. Macro etching of BW BL 50CrMo4 steel, sample transverse to the casting direction.

curved machine, suitable for materials with high carbon and alloy content due to its unique flexion point. Special procedures were used, with strict control of the mechanical conditions of the casting machine (alignment and clearance between segments) and specific control of secondary cooling parameters.

Reference samples were taken from the third slab of each strand to evaluate the results of internal soundness (segregation at the centerline and occurrence of cracks) by macroetching (Figure 6). The level of segregation found was considered suitable for the continuous casting process, especially for high carbon low alloy steels.

Specific tundish cover materials were used to allow for the best absorption of non-metallic inclusions. A fine adjustment of the argon sealing process during continuous casting was carried out to avoid reoxidation. Although the cleanliness level is achieved in the Steelmaking Plant, this was evaluated according to method K of EN 10247 (average of fields) [8], for which hot rolled coils (HRC) samples were used. The results showed no inclusions classified as K1 and above, with a median value of 0.011 inclusions/mm^2 (Figure 7) and no value above the chainsaw bar application requirement (K1≤10), which achieved an excellent K1 index, with a median of 6.5 inclusions/mm^2 (Figure 7). The low fraction of non-metallic inclusions per mm^2 is essential to ensure the durability of the chainsaw bar and to prevent fatigue fractures.

After casting, the slabs were slowly cooled in pits for four days to ensure that no cracks were generated by thermal contraction. This step is very important due to the high hardenability of BW BL 50CrMo4.

3.2 Hot Strip Mill

After cooling, the slabs were loaded into the reheating furnace of the Hot Strip Mill (HSM) at ArcelorMittal Tubarão (Figure 8). Due to the higher carbon content and alloy content of BW BL 50CrMo4 compared to other carbon steels rolled at ArcelorMittal Tubarão, a more cautious approach was adopted in the HSM setup (thickness adjustments, crown, and higher temperatures). After the mathematical model convergence and process stabilization, the setup is gradually adjusted to optimized values of temperature, rolling speed, and crown, avoiding shape defects and achieving the desired

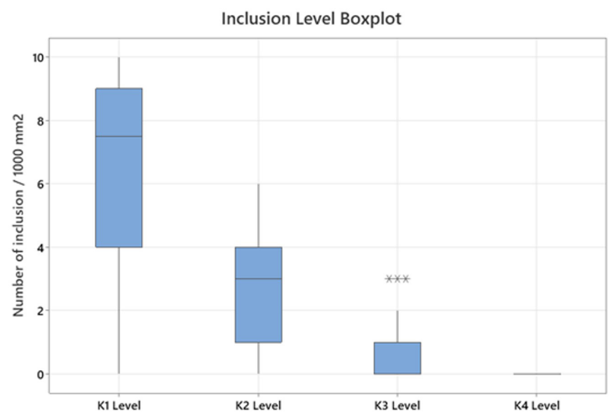


Figure 7. Boxplot of inclusion level for HRC samples.

microstructure (HRC). Nominal thicknesses of 4.80 to 6.30 mm were obtained after stabilization.

For cold rolling, it is necessary to control low crown values and minimize roll wear. Due to the high hardenability of this steel, it is essential to avoid the formation of brittle phases, such as martensite, during hot rolling, strip cooling, and coiling, to prevent breakage and safety hazards. Therefore, areas adjacent to the HSM must be evacuated during the rolling of high carbon steels. The process requires strict control of the finishing delivery temperature (FDT), coiling temperatures (CT), rolling speed, cooling strategy, and adjustment of the laminar flow model. Knowing the time-temperature transformation (TTT) diagrams is crucial to avoid brittle microstructures and intergranular oxidation [4,8]. Ferreira [9] adopted similar precautions to produce high-carbon steels at ArcelorMittal Tubarão for specific applications.

The micrographic analysis of the HRC samples showed a fully pearlitic microstructure (Figure 9), as predicted by the CCT diagram (Figure 2). The interlamellar spacing of pearlite is crucial for the strength of steels. Studies indicate that reducing this spacing increases the yield strength (YS), ultimate tensile strength (UTS), and hardness of steels, but decreases their ductility and impact resistance [9].

Cracks on the surface of the steel generated by grain boundary oxidation could cause premature fatigue failure. Ronqueti's research [10] shows that keeping coiling

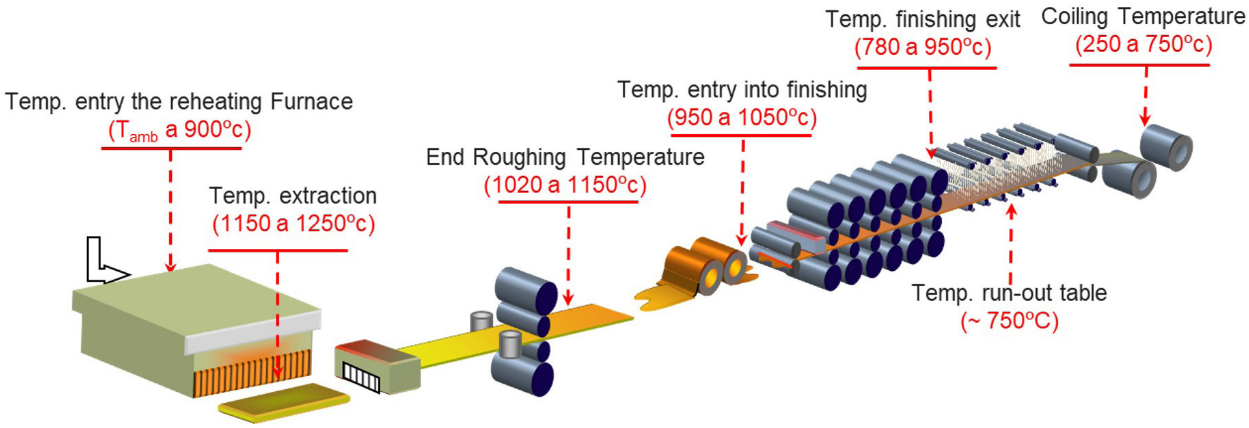


Figure 8. Schematic of the ArcelorMittal Tubarão HSM.

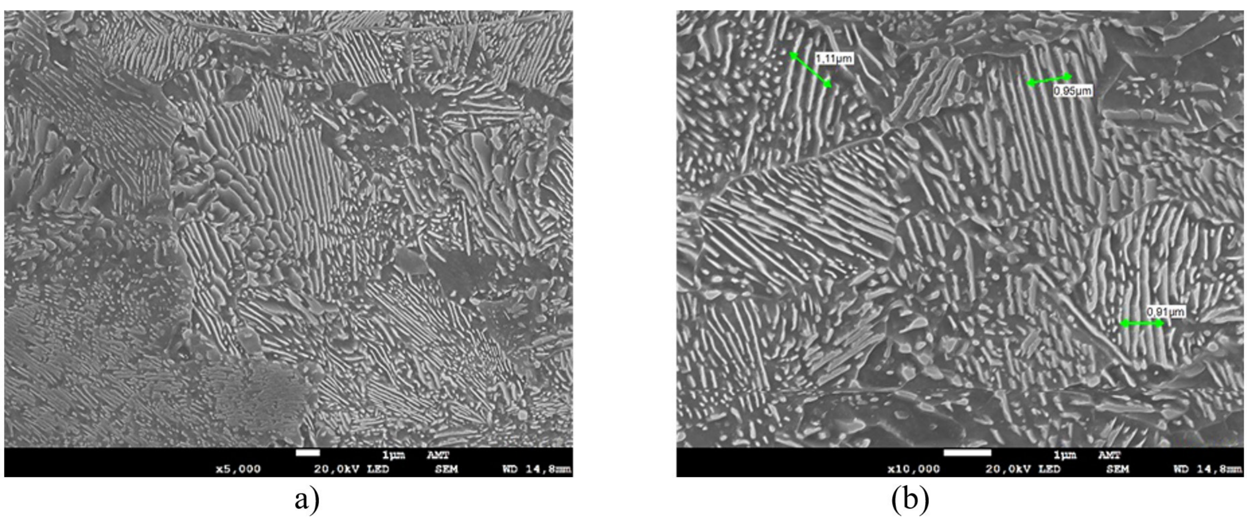


Figure 9. Micrographs of the HRC sample, (a) 5000x and (b) 10000x. SEM – SE – Nital 2%.

temperatures below 600°C reduces this oxidation. Due to the high hardenability of BW BL 50CrMo4 steel, coiling and cooling temperature is a critical challenge in the hot rolling process, demanding strict control to achieve the appropriate microstructure and low grain boundary oxidation. Grain boundary oxidation was not observed in the most sensitive region of the HRC (Figure 10), even though a depth of 5 µm is acceptable.

The mechanical test results of the HRC samples showed coherent values (Table 2) with the chemical composition of the steel studied, directly reflecting the refined and homogeneous microstructure obtained (Figure 9a and 9b).

3.3 Cold rolling and batch annealing

The HRC was pickled in a continuous process where the coil is immersed in a heated solution of hydrochloric acid, followed by rinsing with water, neutralization, drying, and surface lubrication to remove the surface oxides formed during hot rolling. The coil is then cut in a shearing cutting process with circular knives to obtain coils compatible with the widths of the subsequent stages.

The cold rolling process was carried out in a four-high reversible rolling mill, equipped with an automatic gauge control system that ensures compliance with very strict tolerance requirements along the entire length of the strip. The sensitive and precise rolling force regulation system, combined with thickness control by X-ray diffraction, can correct a large part of the thickness

Table 2. Mechanical properties of BW BL 50CrMo4 steel – Longitudinal, base 50mm

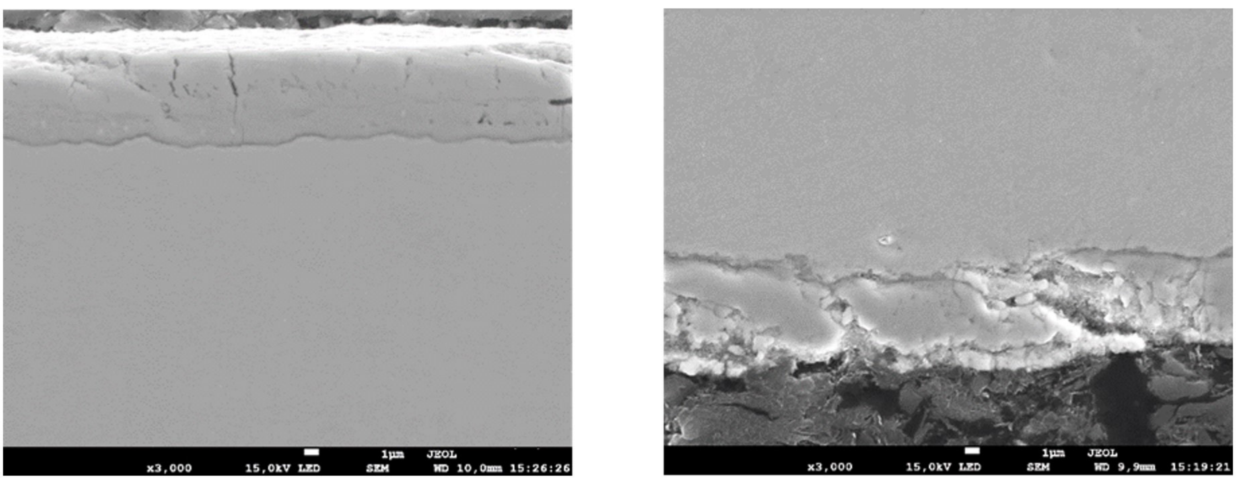
YS (MPa)	UTS (MPa)	E (%)
697	986	12,5

variations from the hot rolling process. CRC's nominal thicknesses was 4.65 mm.

The subcritical batch annealing heat treatment was made in high convection annealing furnaces operated with a protective atmosphere of inert hydrogen gas (H2) 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 the uniformity of the microstructure and mechanical properties. After annealing, the material undergoes a skin pass to determine the final thickness, crown profile, surface finish (appearance and roughness), mechanical properties, and provide shape stability.

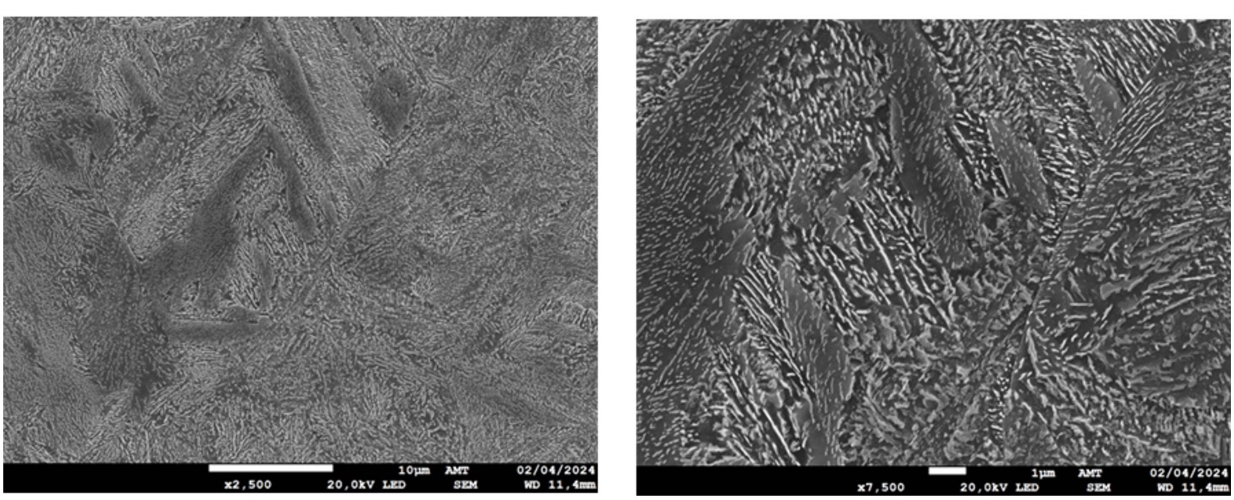
3.4 Austempering in continuous furnaces

Austempering is a heat treatment process used in ferrous alloys, such as steels and cast irons, to enhance their mechanical properties. The material is heated above the critical temperature and rapidly cooled in a salt or oil bath to a specific temperature. The advantages of austempering include the formation of bainite, which increases wear resistance, hardness, and toughness, while reducing distortions and internal stresses compared to conventional quenching and tempering. The process is also more energy-efficient in continuous furnaces due to the precise control of heating and cooling. CRC of BW BL 50CrMo4 grade produced at Waelzholz Brasmetal Laminação after the austempering process achieved the desired microstructure (Figure 11). The samples have a microstructure



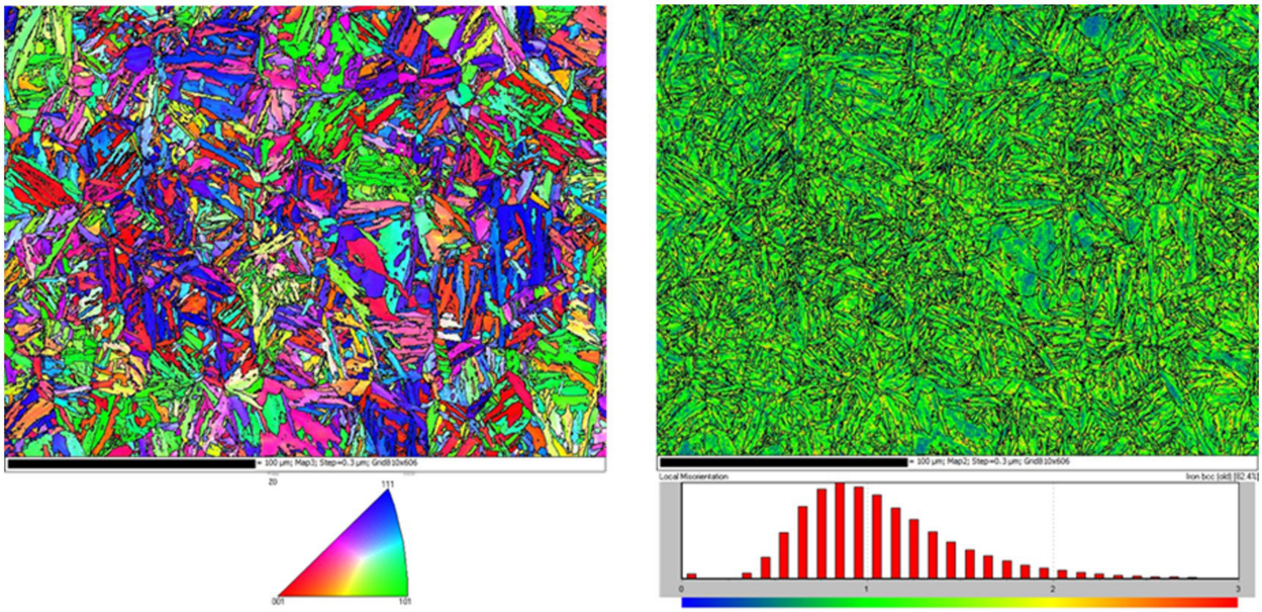
(a) (b)

Figure 10. Micrographs of the surface of the HRC sample, 3000x, (a) Top side and (b) Bottom side. SEM – SE – No etchant.



(a) (b)

Figure 11. Micrographs of BW 50CrMo4 after austempering, (a) 2500x and (b) 7500x. MEV – SE – Nital 2%.



(a) (b)

Figure 12. EBSD of the BW 50CrMo4 sample after austempering, 500x (a) IPF and (b) Local Misiorietation.

Table 3. Mechanical properties of BW BL 50CrMo4 steel along CRC – Longitudinal, base 50mm

Position	YS (MPa)	UTS (MPa)	E	Surface Hardness	¼ Hardness
			(%)	(HRC)	(Vickers)
Head	1170	1350	21	41	410
Middle	1230	1320	17	41	414
Tail	1180	1360	19	41	412

consisting of a fine bainitic matrix associated with dispersed primary carbides that were not dissolved during austenitization. The refinement of the bainite is notable even when observed at 7500x magnification in the SEM – SE.

The Electron Backscatter Diffraction (EBSD) analysis applied to BW BL 50CrMo4 steel, especially after the austempering heat treatment, provided insights into the microstructural changes and their implications on the material's mechanical properties. The analysis revealed the formation of acicular bainite without preferential grain orientation (Figure 12a), along with a high density and distribution of dislocations (Figure 12b), both of which are directly related to the material's strength and toughness. High density indicates greater strength due to work hardening, while a uniform distribution of dislocations suggests good ductility, as localized concentrations can be precursors to fractures.

The hardness measurements (Table 3) on the CRC specimens after austempering showed average results of 41 HRC (402HV) on the surface and 42 HRC (413HV) at ¼ thickness, confirming the microstructural homogeneity. The tensile tests also indicated homogeneity in properties along the length of the CRC BW BL 50CrMo4 produced at Waelzholz Brasmetal Laminação.

4 Conclusions

This work provided a comprehensive review of essential metallurgical knowledge to adjust the steel's microstructure at each stage of the production process, correlating these microstructures with the steel's processing and application. The results obtained highlight the importance of strict control throughout the production process, from the steel mill to the austempering treatment.

- Strict control of the refining and casting parameters of the steel is crucial to ensure the high degree of cleanliness required.

The narrow working window of the hot rolling process demands precise control to both achieve a fine fully pearlitic microstructure and to avoid grain boundary oxidation on the surface.

- The experiments demonstrated that the BW BL 50CrMo4 steel produced at ArcelorMittal Tubarão and Waelzholz Brasmetal Laminação meets crucial metallurgical characteristics for its direct application, in the manufacturing of chainsaw guidebars.

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