

DEVELOPMENT OF HIGH-CARBON LOW-ALLOY STEEL (BW BL 50CRMO4) AT ARCELORMITTAL TUBARÃO AND WAEZHOLZ BRASMETAL LAMINAÇÃO FOR DIRECT APPLICATION IN CHAINSAW GUIDE BAR*

Henrique Severiano de Jesus¹
Fernando Generoso Neiva Ferreira²
Eduardo Alves Machado³
Fabiano Almir Barbosa⁴
Juliano Braz Possati⁵
Marcelo Urdapilleta Rodrigues⁶
Maurício Franco Bomfim⁷
Marina de Lima Barroso⁸
Daniel Augusto Ferro⁹
Thomas Frank¹⁰

Abstract

New alternative steels are continually frequently being proposed to reduce costs and improve industry competitiveness. This study presents the development of high-carbon low-alloy steel, BW BL 50CrMo4, at ArcelorMittal Tubarão and Waelzholz Brasmetal Laminação, 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 the re-rolling. This steel is widely used in components that require high mechanical strength, cleanliness, 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 guidebar. 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 on 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 guidebar; ArcelorMittal Tubarão; Waelzholz Brasmetal Laminação.

- ¹ Mechanical Engineer, Product Development Specialist, ArcelorMittal Tubarão, Serra, ES, Brazil.
- ² M.Sc., Metallurgical Engineer, Product Development Specialist, ArcelorMittal Tubarão, Serra, ES,
- ³ M.Sc., Metallurgical Engineer, Client Technical Support Specialist, ArcelorMittal Tubarão, Serra,
- ⁴ M.Sc., Metallurgical Engineer, Continuous Casting Process Specialist at ArcelorMittal Tubarão,
- ⁵ M.Sc., Metallurgical Engineer, Hot Rolling Process Specialist at ArcelorMittal Tubarão, Serra, ES, Brazil.
- ⁶ M.Sc., Mechanical Engineer, Sales Executive, ArcelorMittal Tubarão, Serra, ES, Brazil.
- ⁷ Metallurgical Engineer, Engineering, Purchasing and Production Planning Manager at Waelzholz Brasmetal Laminação, Diadema, SP, Brazil.
- ⁸ Materials Engineer, Purchasing Engineer, Waelzholz Brasmetal Laminação, Diadema, SP, Brazil
- ⁹ M.Sc., Mechanical Engineer, Development and Technical Support Engineer, Waelzholz Brasmetal Laminação, Diadema, SP, Brazil.
- ¹⁰ Materials Engineer, Development and Technical Support Supervisor, Waelzholz Brasmetal Laminação, Diadema, SP, Brazil.

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 hardness 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.



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.

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 the DIN EN 10083-3 [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 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]

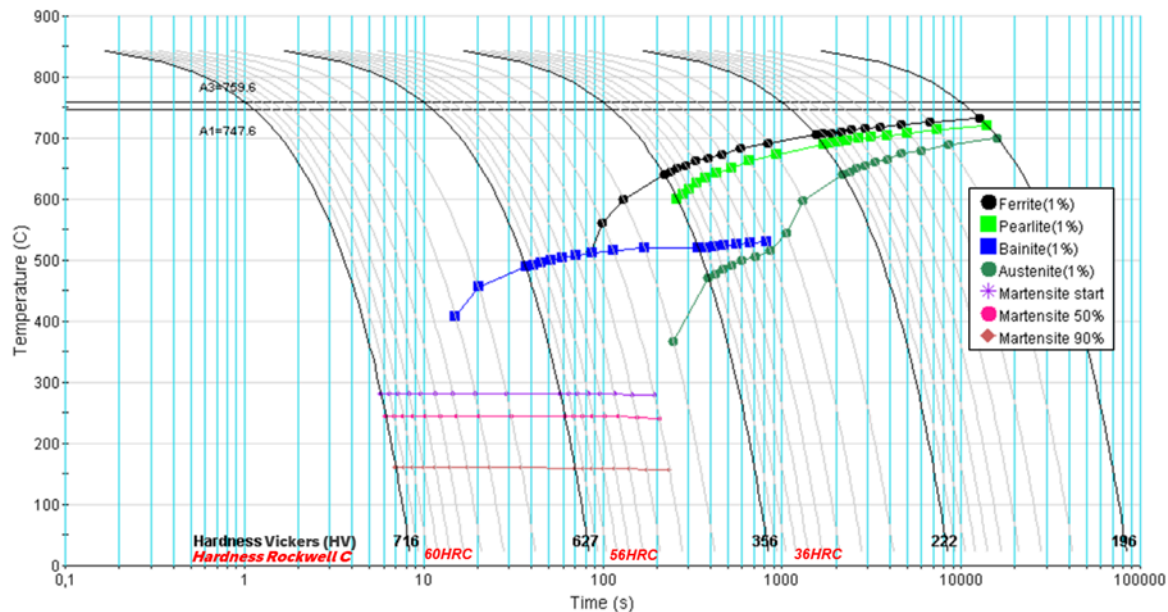


Figure 2. Continuous Cooling Transformation Diagram (CCT) BW BL 50CrMo4 by JMatPro V.13.

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 percentage 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

Material

The steel alloy 50CrMo4 – DIN EN 10083-3 [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), shown in table 1, its production is very complex in every step of the process.

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 / Plate reheating / Hot rolling / Packaging), Figure 3, and processed by Waelzholz Brasmetal Laminação (Pickling / Slitting / Cold rolling / Annealing / Austempering / Skin pass / Cutting / Packaging), Figure 4.

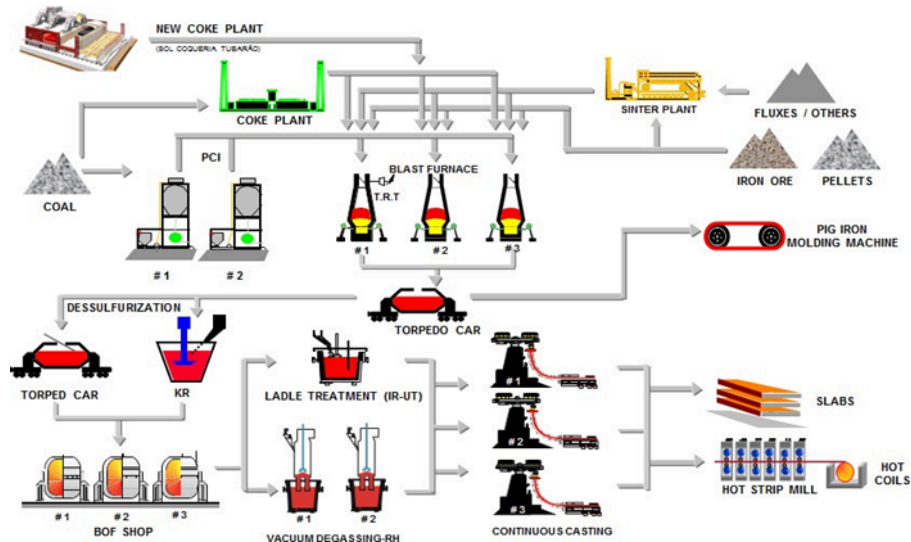


Figure 3. ArcelorMittal Tubarão production flowchart.

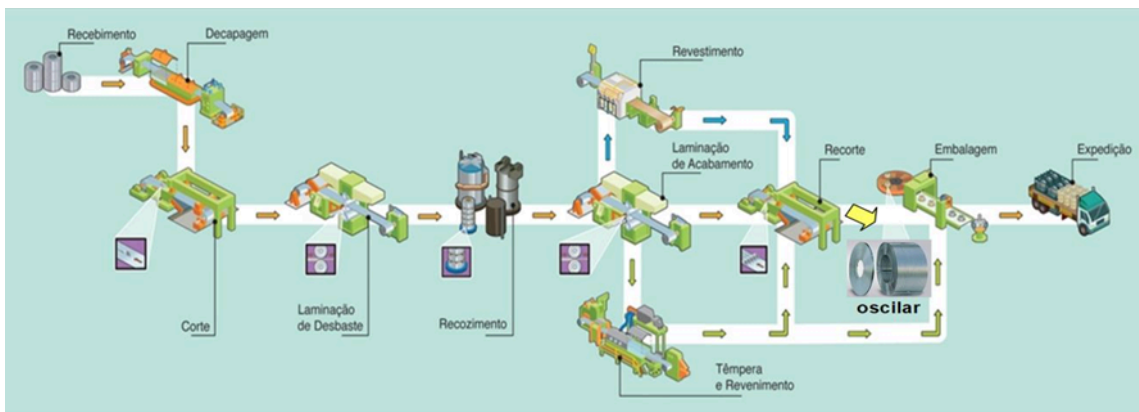


Figure 4. Production flowchart of BW BL 50CrMo4 steel at Waelzholz Brasmetal Laminação (main line without auxiliary processes)

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

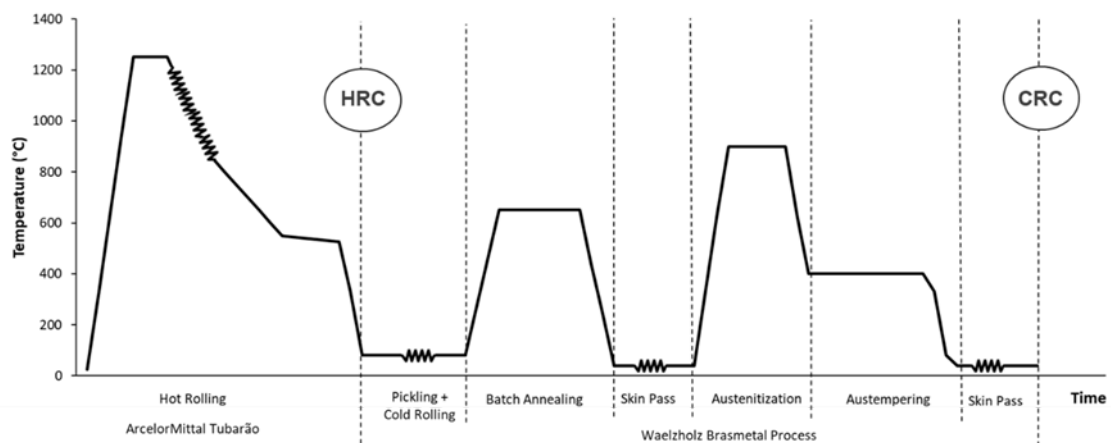


Figure 5. Thermomechanical process flow in BW BL 50CrMo4 steel until the final product.

2.1 Methods

2.1.1 Macro attack test

Slab samples (transverse and longitudinal) were prepared as follows: gas cutting, milling for surface leveling, and sanding using a pendulum sander. The samples were etched with ammonium persulfate solution (25%) for 10 seconds, then washed with water and dried with compressed air, inspected, and photographed.

2.1.2 Microstructural Characterization

Both hot-rolled (HRC) and cold-rolled (CRC), were traditionally prepared for microstructural characterization: cutting; hot mounting (Bakelite), grinding (silicon carbide: from 100 to 1200 mesh, successively, using water); manual polishing (3 μ m and 1 μ m diamond paste). For morphological analysis of the microstructure, the samples were etched 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.

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 [4] 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 6671 [5].

3 RESULTS AND DISCUSSION

3.1 Steelmaking

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

- Maintain the sulfur content below 30 ppm in Si-Killed steels without using desulfurization in the secondary refining station.

- Keep the 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 breakage 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, are made to maintain the low sulfur content. During thermoheating, the aluminum content is controlled not to 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 casted using ArcelorMittal Tubarão 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 quality (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.



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

To ensure a low level of inclusions, specific tundish cover materials were used to allow for the best absorption of these inclusions and the fine adjustment of the argon sealing process during continuous casting 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) [6], for which HRC samples were used. The results showed no inclusions classified as K1 and above, with a median value of 0.011 inclusions/mm² (Figure 7) and no value above the chainsaw bar application requirement ($K1 \leq 10$), which achieved an excellent K1 index, with a median of 6.5 inclusions/mm² (Figure 7). The low percentage of non-metallic inclusions per mm² is essential to ensure the durability of the chainsaw bar and to prevent fatigue fractures.

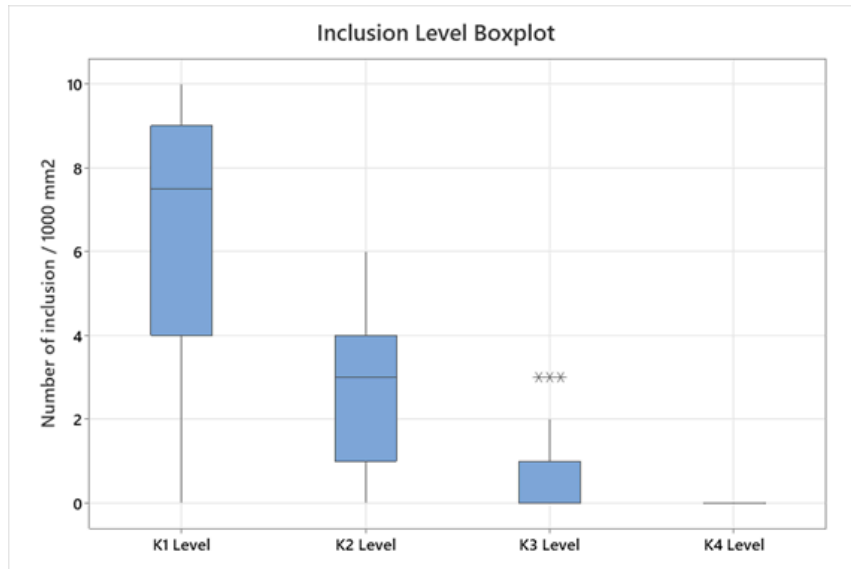


Figure 7. Boxplot of inclusion level for HRC samples.

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

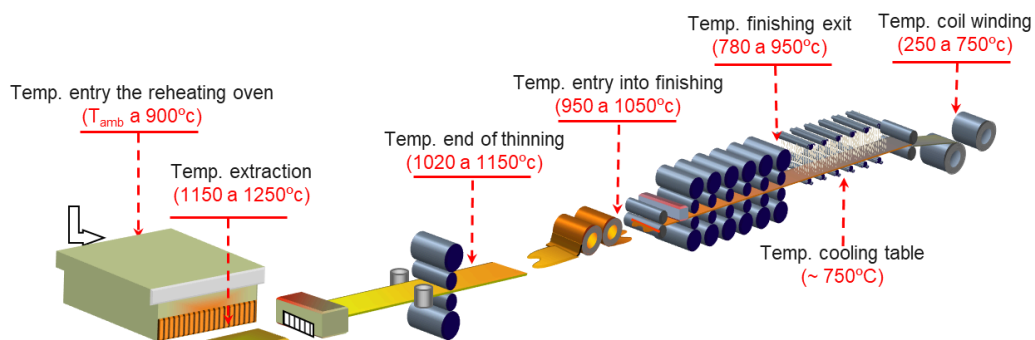


Figure 8. Schematic of the ArcelorMittal Tubarão HSM.

For cold rolling, it is necessary to control low crown values and minimize roll wear. Due to the high hardenability of the 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. [7,8] Ferreira 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].

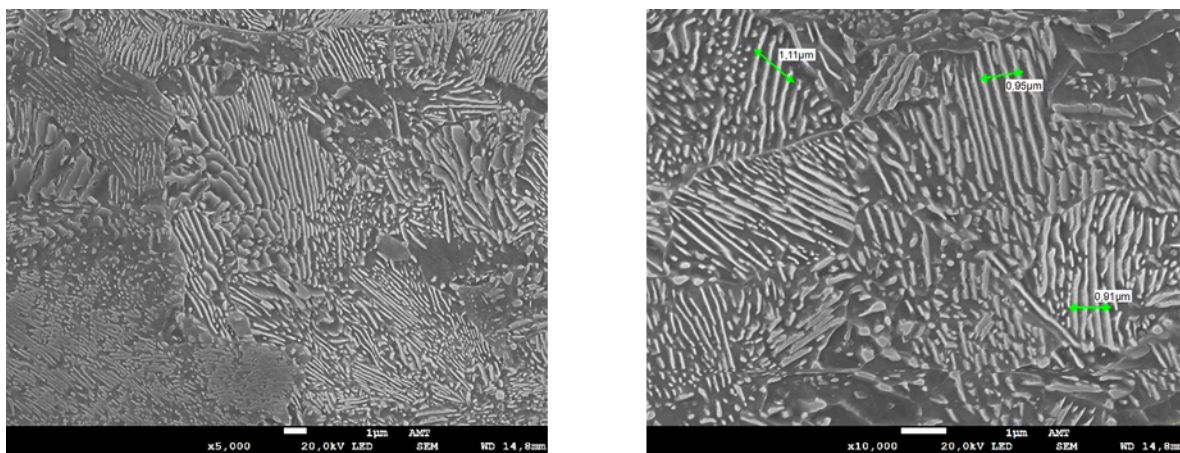


Figure 9. Micrographs of the HRC sample, (a) 5000x and (b) 10000x. MEV – SE – Nital 2%.

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

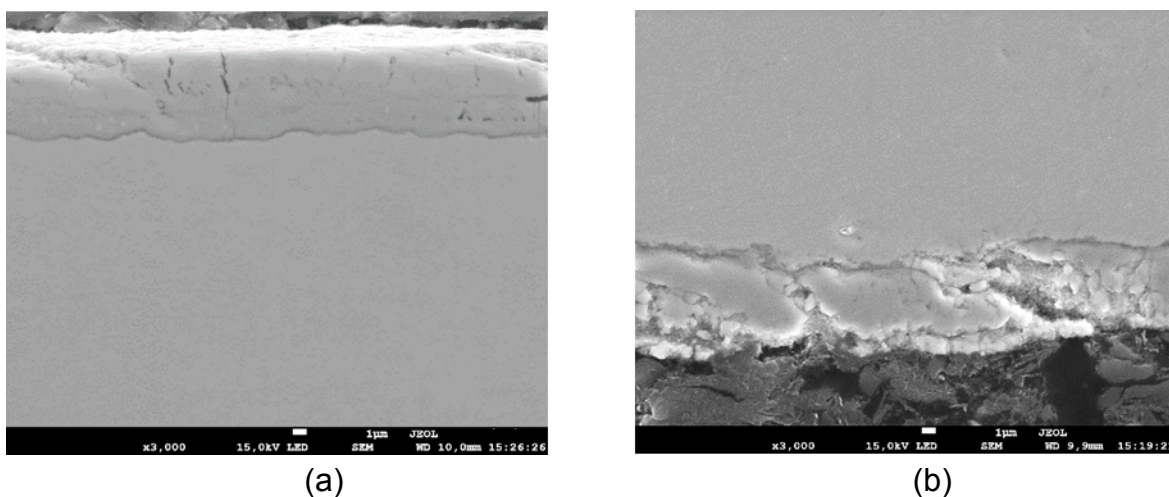


Figure 10. Micrographs of the surface of the HRC sample, 3000x, (a) Top side and (b) Bottom side. SEM – SE – Sem etchant.

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).

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

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

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 thickness control system that ensures compliance with very strict tolerance requirements over 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 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 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 continuous 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 consisting of a fine bainitic matrix associated with dispersed primary carbides that weren't dissolved during austenitization. The refinement of the bainite is notable even when observed at 7500x magnification in the SEM – SE.

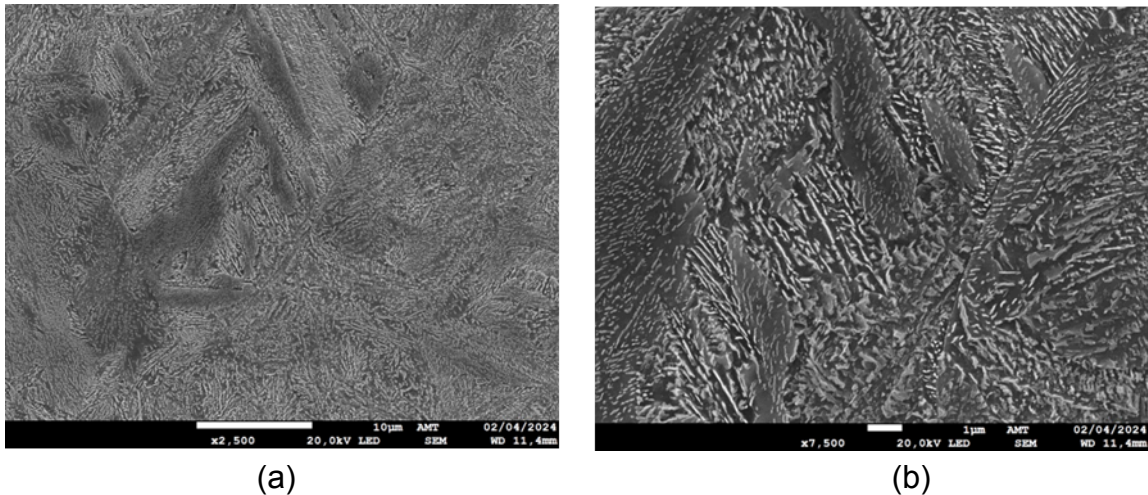


Figure 11. Micrographs of BW 50CrMo4 after austempering, (a) 2500x and (b) 7500x. MEV – SE – Nital 2%.

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 reinforcement, while a uniform distribution of dislocations suggests good ductility, as localized concentrations can be precursors to fractures.

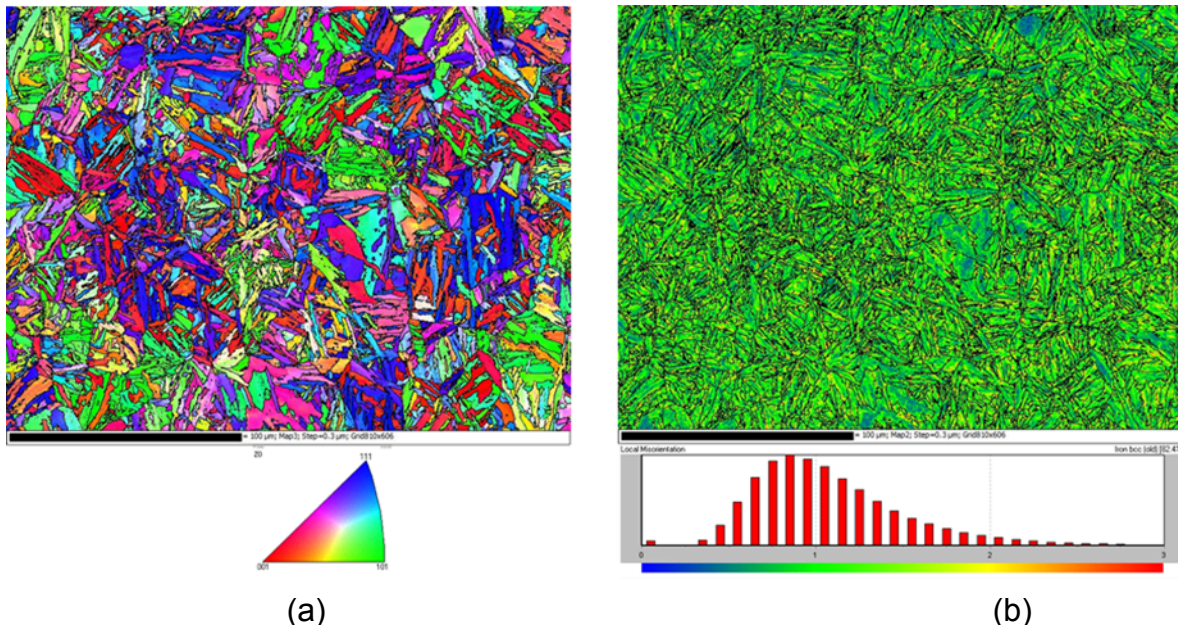


Figure 12. EBSD of the BW 50CrMo4 sample after austempering, 500x (a) IPF and (b) Local Misorientation.

The hardness measurements on the CRC specimens after austempering showed average results of 41HRC (402HV) on the surface and 42HRC (413HV) at $\frac{1}{4}$ 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.

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

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

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.

REFERENCES

- 1 50CrMo4 Steel DIN EN 10083-3: 2006 – Table 8, p.21.
- 2 Stickels C.A. “Carbide Refining Heat Treatments for 52100 Bearing Steel” Metallurgical Transactions A, V.5, p. 865 – 874 (1974)
- 3 Metals Handbook, Vol. 1, Properties and Selection: Iron, Steel and High-Performance Alloys, 10a. ed., ASM International (2004), pp. 986-992.
- 4 ABNT NBR ISO 6892-1 – Materiais metálicos — Ensaio de Tração – Parte 1: Método de ensaio à temperatura ambiente. Rio de Janeiro, RJ, Brazil, 2013.
- 5 ABNT NBR NM ISO 6507-1 – Materiais metálicos – Ensaio de dureza Vickers – Parte 1: Método de ensaio. Rio de Janeiro, RJ, Brazil, 2008.
- 6 EN 10247 – Microscopic examination of special steels using diagrams to assess the content of non-metallic inclusions. Deutsches Institut fur Norming. Berlin, 2007.
- 7 Ferreira F.G.N. et al. Desenvolvimento de aço alto carbono baixa liga na Arcelormittal Tubarão e na Waelzholz Brasmetal Laminação para aplicação final em corrente de motosserra. 54^o Seminário de Laminação e Conformação de Metais. Associação Brasileira de Metalurgia, Materiais e Mineração. São Paulo, Brazil. 2017.
- 8 Ferreira F.G.N. et al. Development of Cr and V alloyed high carbon sheet steel (BW BL 50CrV4) at ArcelorMittal Tubarão and Waelzholz Brasmetal for diaphragm spring. 11th International Rolling Conference. Associação Brasileira de Metalurgia, Materiais e Mineração. São Paulo, Brazil. 2019.
- 9 WU, K.M and BHADSHIA, H.K.D.H. Extremely Fine Pearlite by Continuous Cooling Transformation. Scripta Material, Vol.67, 2012, p. 53-56.
- 10 Ronqueti, L. A. et al. Study of grain boundary oxidation of high alloyed carbon steels at coiling temperature. 53^o Seminário de Laminação da ABM, RJ, Brasil, Anais, 2016.