DEVELOPMENT OF CR AND V ALLOYED HIGH CARBON SHEET STEEL (BW BL 50CRV4) AT ARCELORMITTAL TUBARÃO AND WAELZHOLZ BRASMETAL FOR DIAPHRAGM SPRING*

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Abstract

Spring steels are usually classified as medium to high carbon low alloy steels with very high yield strength, enabling the part to return to its original shape regardless of significant bending or twisting. Despite the fact that plain carbon steels are suitable for small springs, larger and high performance springs usually requires alloy steels such as Cr-V or Si-Mn in order to achieve an even microstructure throughout the cross section. Clutch diaphragm spring is a high performance part that requires very good cleanliness and microstructure homogeneity, thus requiring an alloy steel. In this paper was studied, in an industrial scale, the process parameters and critical characteristics for the development of a Cr and V alloyed high carbon sheet steel for the production of clutch diaphragm spring. The steel was characterized throughout the entire process (casting, hot rolling, cold rolling + batch annealing and heat treated) using tensile test, hardness test, optical microscopy (OM) and scanning electron microscopy (SEM) to assess the mechanical and metallurgical properties of the studied steel. The results have shown the material's microstructure evolution after each main stage of the process, from a ferrite-bainite/perlite based microstructure as hot band to fully spheroidized as cold-rolled/annealed and then fully martensitic as ready-to-use part.

Keywords: High carbon sheet steel; 50CrV4; Diaphragm spring; ArcelorMittal Tubarão; Waelzholz Brasmetal.

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1 INTRODUCTION

Clutches are designed to engage and disengage the transmission system from the engine when a vehicle is being driven away from a standstill and when the gearbox gear changes are necessary. The gradual increase in the transfer of engine torque to the transmission must be smooth. Once the vehicle is in motion, separation and take-up of the drive for gear selection must be carried out rapidly without any fierceness, snatch or shock. [1]

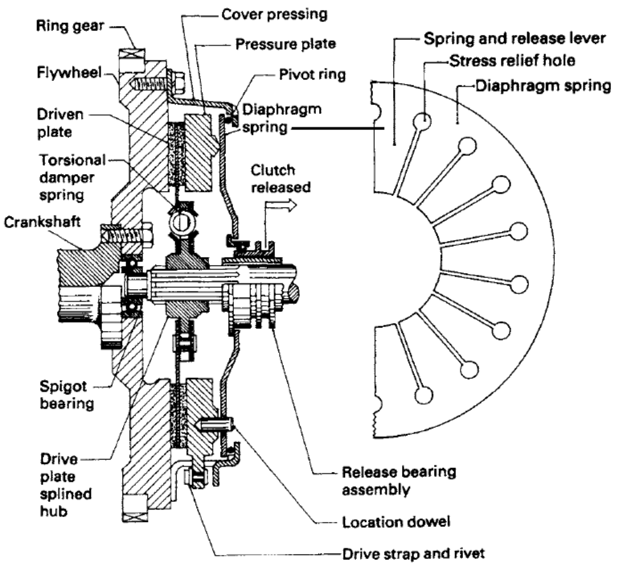


Figure 1. Diaphragm single plate pull type clutch, showing a cut-in-half diaphragm. Adapted from Heinz (2002)

The main components of the pressure plate assembly are a cast iron pressure plate, a spring steel diaphragm disc and a low carbon steel cover pressing (Figure 1). The diaphragm is made to pivot between a pivot ring positioned inside the rear of the cover and a raised circumferential ridge formed on the back of the pressure plate. The diaphragm spring takes the shape of a dished annular disc. The inner portion of the disc is radially slotted, the outer ends being enlarged with a circular hole to prevent stress concentration when the spring is deflected during disengagement (Figure 1). These radial slots divide the disc into many inwardly pointing fingers which have two functions, firstly to provide the pressure plate with an evenly distributed multileaf spring type thrust, and secondly to act as release levers to separate the driven plate from the sandwiching flywheel and pressure plate friction faces. [1]

Spring steels are usually classified as medium to high carbon low alloy steels with very high yield strength, enabling the part to return to its original shape regardless of significant bending or twisting. Despite the fact that plain carbon steels are suitable for small springs, larger and high performance springs usually requires alloy steels such as Cr-V or Si-Mn in order to achieve an even microstructure throughout the cross section. As example of DIN 50CrV4 grade (Figure 2), that contains Cr and V, shows a very good operational window for quenching. Clutch diaphragm spring is classified as a high performance part that requires very good cleanliness and microstructure homogeneity, thus demanding an alloy steel.

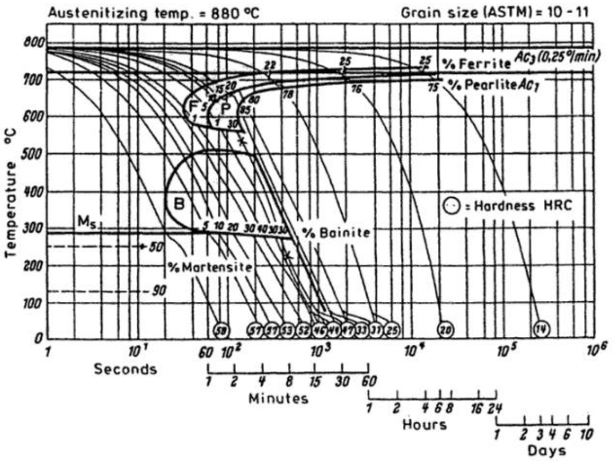


Figure 2. Continuous cooling transformation (CCT) diagram of DIN 50CrV4 steel. [2]

As required by the application, spring steels must have a high yield stress/tensile stress ratio to withstand great elastic deformation, consequently the desirable microstructure is fully martensitic (usually tempered) or, in some cases, fully bainitic. Rios [3] describes the martensitic transformation, also known as "military transformation", as an essentially adiffusional transformation, hence without long distances diffusion (larger than network parameter) but through the coordinated small movement (smaller than network parameter) of many atoms simultaneously. This transformation occurs with change of shape and volume, which significantly increases the density of crystalline defects (*e.g.* dislocations), producing microstructures of high mechanical resistance. After quenching, the tempering process temporarily allows solid solution atoms to migrate out of the supersaturated network, relieving a portion of the stress generated during martensitic transformation thus improving elongation, toughness and fatigue performance of final microstructure.

2 MATERIAL AND METHODS

2.1 Material

The BW BL 50CrV4 steel was developed to fit diaphragm spring application, showing good formability and hardenability as cold rolled and, post quenching and tempering, high hardness and fatigue resistance. Due to its high alloying content (C, Cr and V), shown in Table 1, its production is very complex in every production process.

Table 1. Chemical composition BW BL 50CrV4

C (%)	Mn (%)	Si (%)	Cr (%)	V (%)
0.50-0.55	0.70-1.20	0.10-0.40	0.90-1.10	0.10-0.15

The steel was produced as hot rolled coils (HRC) at ArcelorMittal Tubarão (Steelmaking / Continuous casting / Slow cooling / Slab reheating / Hot rolling / Packing), produced as cold rolling coils (CRC) at Waelzholz Brasmetal Laminação (Pickling / Longitudinal cut / Cold rolling / Batch annealing / Skin pass / Packing) and shaped into ready-to-use part at the Diaphragm Spring producer (Blank cutting / Hot Stamping / Tempering / Shot Peening). To achieve the performance needed for diaphragm spring, this steel is produced through a very specific steelmaking route (Figure 3) to ensure low levels of inclusions to attend client's specification.

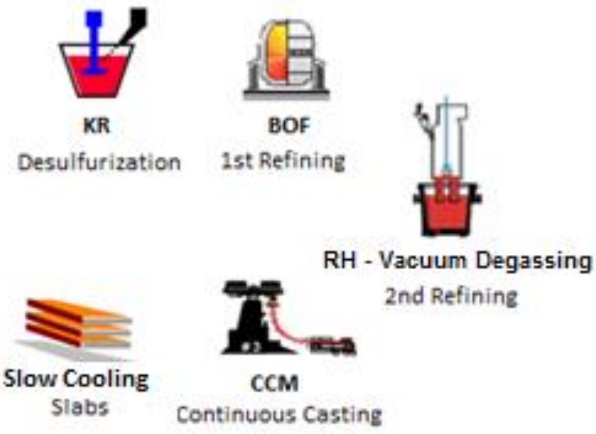


Figure 3. Slab production stream at ArcelorMittal Tubarão to guarantee low inclusion levels.

Figure 4 summarizes the thermo mechanical process applied to the studied steel, also pointing which stages full characterization samples were taken (HRC, CRC and ready-to-use part). In addition to these stages, an induction heating followed by forced air quenching was made at the inner portion of the spring lever to further increase hardness, once this portion is the most wear stressed part of the diaphragm spring.

2.2 Methods

Slab samples (transversal and longitudinal) were gas cut, surface leveling by milling and sanding using swinging sander, so the samples were etched with ammonium persulfate solution (25%) for 10 seconds, washed with water and dried with forced air. The samples surface is then inspected and recorded.

HRC, CRC and ready-to-use part samples were prepared for microstructural analysis as follows: cutting, mounting in resin, sanding (silicon carbide from 100 to 1200 mesh, using water), polishing (3µm and 1µm diamond paste). To analyze

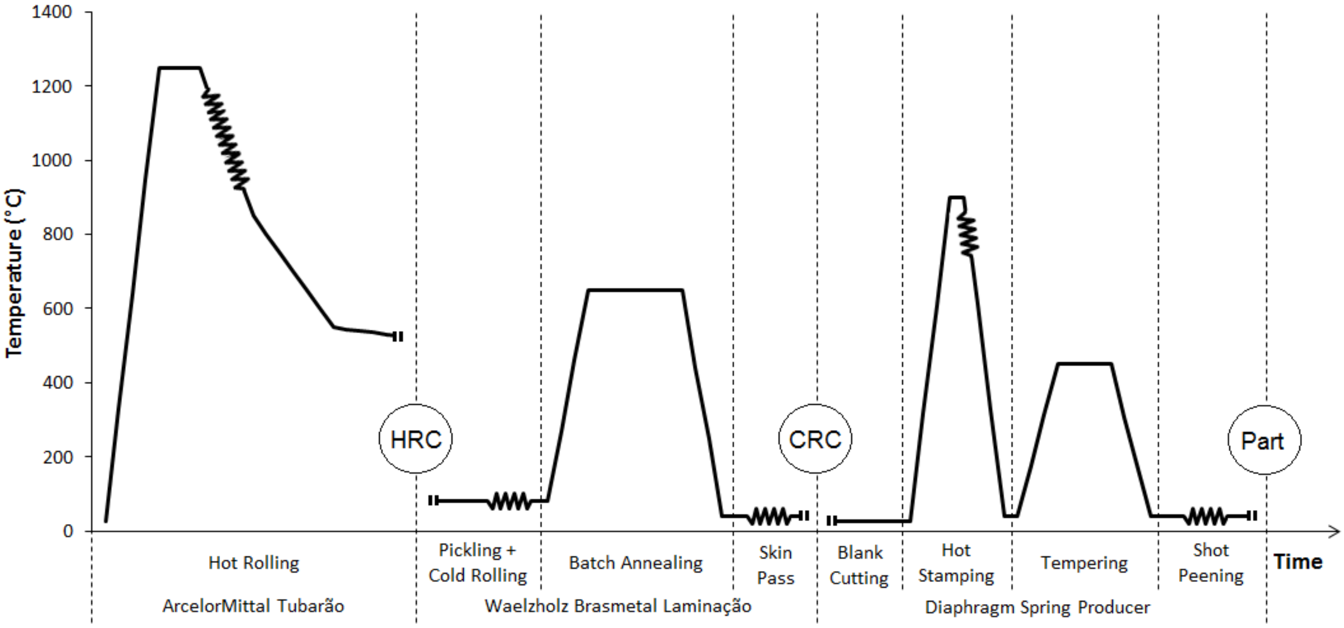


Figure 4. BW BL 50CrV4 steel thermo mechanical process stream for Diaphragm Spring production.

microstructure morphology, the samples were etched by immersion using Nital 2% for 30 seconds or until the surface is darksome [4], whereas, to analyze internal cleanliness (inclusion level) and intergranular oxidation depth, no etchant was used in order to neither avoid masking nor accentuate oxidation depth perception. Two microscopes were used: Optical Microscope (OM), Leica DM6000 (light filed to evaluate inclusion level), accordingly to EN 10247 [5] method K, and Scanning Electron Microscope (SEM), JEOL JSM7100F FEG (12kV, 13.7-15.7mm working distance, secondary electron detector to evaluate morphology and backscatter to analyze intergranular oxidation).

Tensile tests were performed accordingly to ABNT NBR ISO 6892-1[6] (L_0 = 50mm) using ZWICK Z250 machine and contact strain-gauge and Rockwell hardness tests (B and C) were carried out accordingly to ABNT NBR 6671[7] using Emco M4U-025 durometer. Due to shape and size limitations, these techniques were only used on HRC and CRC samples. To assess ready-to-use part sample, Vickers micro hardness tests were done along the spring lever accordingly to ABNT NBR NM ISO 6507-1[8] using Shimadzu HMV-G durometer.

3 RESULTS AND DISCUSSION

3.1 Steelmaking

BW BL 50CrV4 steel grade presents the following challenges regarding steel refining:

- Ensure maximum sulfur content of 50ppm in Si-Killed steel, through a production route that does not consider a desulfurization step in a secondary refining station.
- Ensure maximum aluminum content of 0.015% at RH Vacuum Degasser, considering the chemical heating process in this type of equipment.
- Ensure low oxygen level in liquid steel during casting that could led to bubbles and porosities on casted slabs.
- Ensure a high level of liquid steel cleanliness.

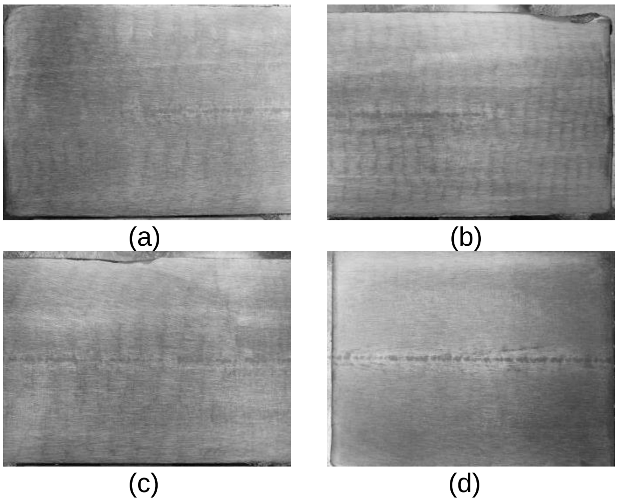
The steelmaking process starts at KR (Kambara Reactor), Figure 3, where the hot metal (pig iron) was desulfurized to a maximum sulfur content of 10 ppm. Meanwhile the scrap that was used in the converter process was rigorously selected. Primary refining at the converter was conducted in order to guarantee a low sulfur reversion during oxygen blow. Ferroalloys additions, especially recarburizers, were carried out also to guarantee low sulfur content. During heat taping, a strict control of the aluminum addition was made to make sure not to exceed the maximum allowed content. After heat taping, still at the converter bay, liquid steel desulfurization step takes place to further decrease sulfur content.

RH Vacuum Degasser treatment first considers a chemical heating step, using exclusively FeSi. Then, the challenge was to ensure the maximum aluminum content of 0.015%. High aluminum contents do not meet the customer demands and very low contents can cause bubbles and porosities in the slabs and even cause a breakout during casting. To finish steel refining, the heat passes through a calcium addition step through the injection of CaSi wires.

Three experimental heats were casted using curved machine at ArcelorMittal Tubarão, which is the most recommended machine for casting high carbon materials with high alloy content due to its single bending point.

Special procedures were used to produce these heats, highlighting the strict control of the mechanical conditions of the casting machine (alignment and gap between segments) and specific control of the secondary cooling parameters.

Reference samples were taken from the third casted slab from each strand to evaluate the internal quality results (centerline segregation and crack occurrences) by macro etching (Figure 5). No longitudinal, transversal, side or corner cracks (Figures 5a, b and c) and normal centerline segregation (Figure 5d) were found, which is inherent of the continuous casting process, especially for high carbon steels with high alloy content.


(a) (b)

(c) (d)

Figure 5. BW BL 50CrV4 three heats representative macro etching photographs, transversal (a) left side, (b) right side, (c) middle and (d) longitudinal.

To assure low inclusion level, specific tundish cover materials were used to allow the better absorption of these inclusions fine tuning of the argon sealing process during the continuous casting of the heats.

After casting, the slabs were slowly cooled in pits for 4 days to ensure no cracks would be generated by thermo contraction. This step is very important due to BW BL 50CrV4 high hardenability.

Although cleanliness level is achieved at Steelworks, it was assessed accordingly to EN 10247 method K (average of fields), hence HRC samples were used. Results have shown almost no inclusions classified as K4 and above, finding a median value of 0,615 inclusions/mm² (Figure 6) and no value above diaphragm spring application requirement (K4≤30), on the other hand a reasonable K1 index was observed, median of 38,025 inclusions/mm² (Figure 6), probably related to inclusion globalization by CaSi addition at vacuum degasser treatment and favorable inclusion flotation at continuous casting.

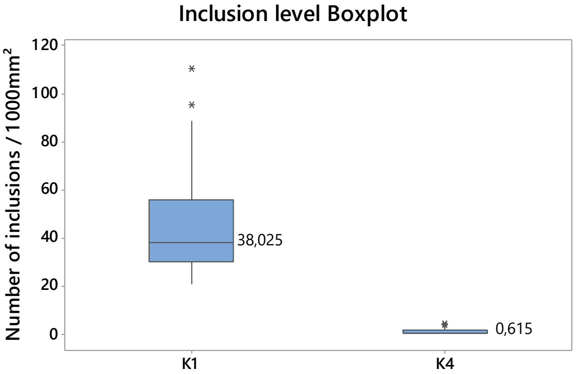


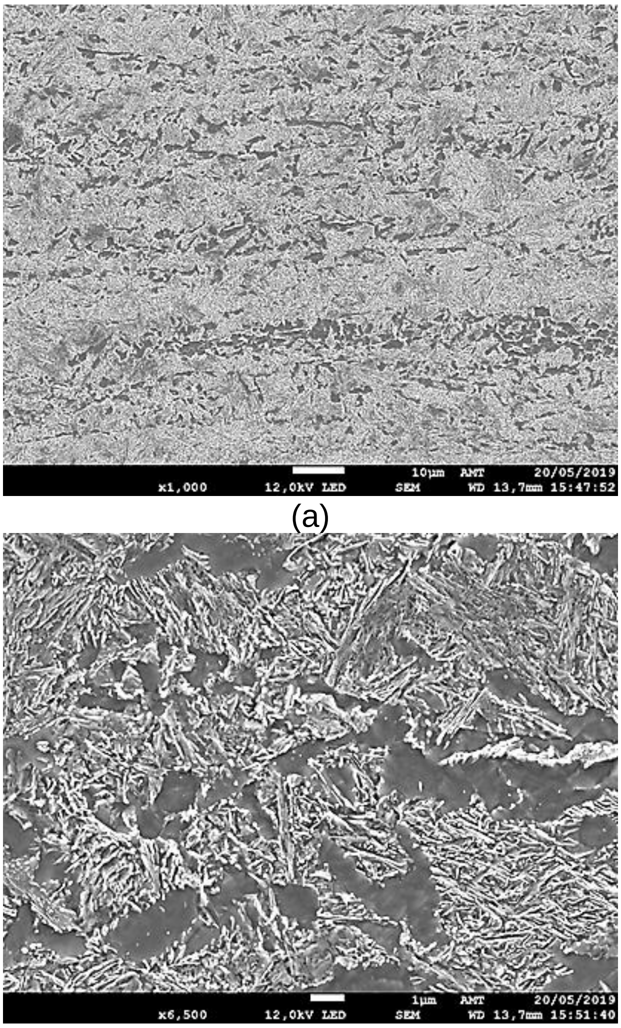
Figure 6. Inclusion level Boxplot for HRC samples.

3.2 Hot Rolling

After casting, the slabs were slowly cooled in pits for 4 days and then charged into the Hot Strip Mill reheating furnace. BW BL 50CrV4 was the first high carbon Cr-V alloyed steel hot rolled at ArcelorMittal Tubarão, thus it was taken a more conservative approach regarding HSM setup (e.g. higher thickness, crown and temperatures). As the mathematical model converges and the process stabilizes, the setup is gradually changed to enhanced values of temperature, rolling speed, crown to prevent shape defects as coil sagging and wedge, for example, and attending the desired microstructure as HRC. After stabilizing the Hot Rolling process, HRC nominal thickness from 2.65 to 7.00mm were obtained.

To attain a suitable transversal profile for next process, cold rolling (Figure 4), with this high hot deformation resistance steel it is necessary to aim low crown values and restrain scheduling conditions to produce it with low roll wear conditions at roughing and finishing mill.

Due to its high hardenability it’s very important to assure that no brittle phases (e.g. martensite) will be formed during hot rolling, run out table (ROT) cooling nor coiling that could lead to material shattering, projecting brittle shards that represents a safety hazard. Therefore, as a safety measure, it is mandatory the evacuation of HSM adjacent areas during rolling of high carbon steels at ArcelorMIttal Tubarão. In addition the hot rolling process is carried out under a very tight control of finishing delivery temperature (FDT), coiling temperatures (CT), rolling speed, cooling strategy and laminar flow modeling adjustment. To define such parameters it is imperative to know the steel time – temperature – transformation (TTT) diagrams to find the optimal combination of parameters to avoid both brittle microstructure and intergranular oxidation at the strip’s surface.

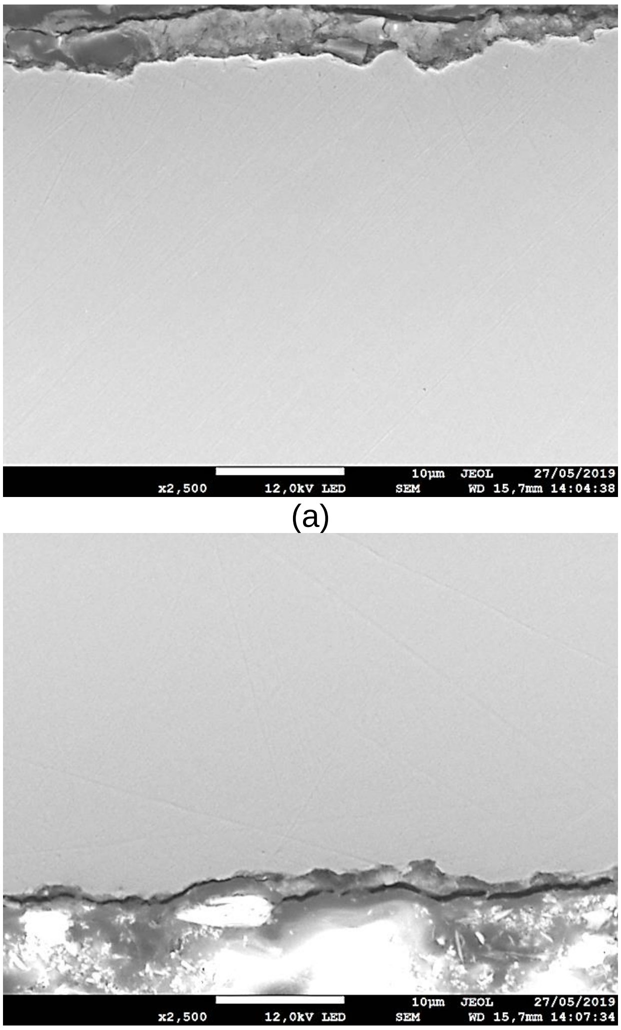


(a)

(b)

Figure 7. Micrographs of Hot Rolled sample, (a) 1000x and (b) 6500x. SEM – SE – Nital 2%.

Micrographic analysis of HRC samples have shown microstructure formed mostly by bainite, small portions of degenerated perlite and ferrite islands (Figure 7), as expected based on CCT diagram (Figure 2). On the other hand, Alves [9] and Ferreira [10] have conducted similar industrial trials with even higher carbon content grades with lower Cr and no V alloying, resulting microstructures composed mainly by fine perlite associated with small ferrite islands. This difference could be associated to high carbide-forming alloying elements, in this case Cr and V, which delay austenite decomposition between 400-700°C and speed up bainitic transformation below 400°C [2].



(b)

Figure 8. Micrographs of Hot Rolled sample near the surface, (a) Top side and (b) Bottom side. SEM – SE – No etchant.

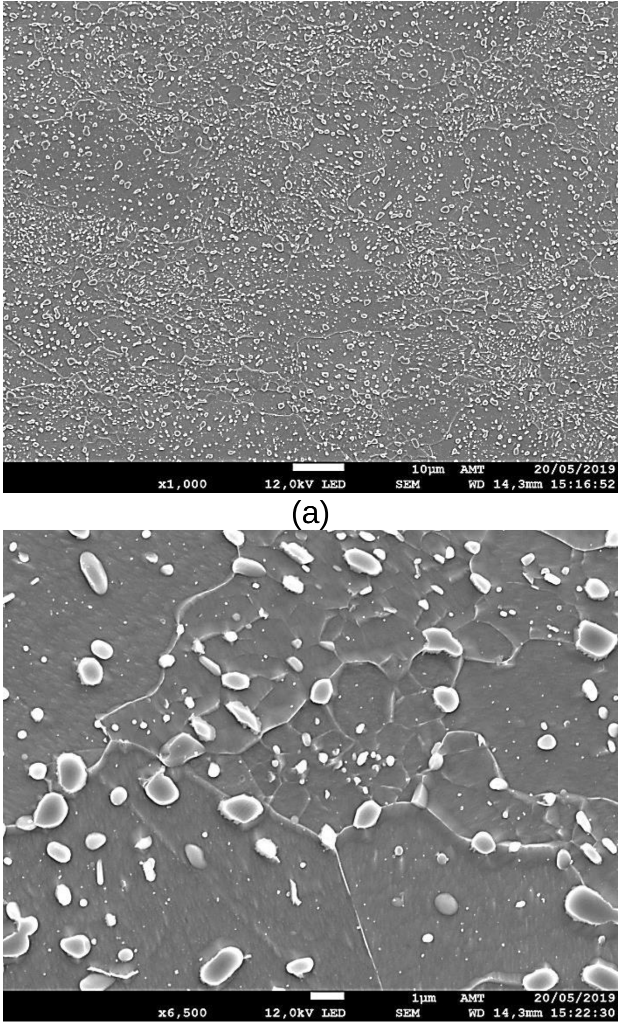
Ronqueti [11] have studied selective oxidation of high alloyed carbon steels at coiling temperature and revealed that coiling temperatures should be as lower as possible below 600°C to mitigate grain boundary oxidation. Therefore, combined with high hardenability of BW BL 50CrV4, coiling temperature/coil cooling becomes one of the main challenges of hot rolling process with a very narrow work window to combine appropriate microstructure and low grain boundary oxidation. No grain boundary oxidation was observed at the most susceptible portion of the HSM (Figure 8), middle of the length and center of the width, even though a 5µm depth at this position is tolerable.

3.3 Cold Rolling and Batch Annealing

HRC were shipped to Waelzholz Brasmetal Laminação to be pickled, slitted, cold rolled, batch annealed and skin passed (Figure 4).

After pickling and slitting, which does not generate any significant metallurgical change on the steel, the HRC were cold rolled using a four-high reversible mill with 280mm diameter working cylinders, cooled by aqueous emulsion. The resulting CRC nominal thicknesses were from 1.90 to 6. Afterwards, CRC went under subcritical annealing in a high convection (100% hydrogen atmosphere) batch annealing furnace to promote microstructure recrystallization and cementite spheroidization, followed by approximately 1.00% elongation skin pass. Combining tight thickness and crown control both at Hot Strip Mill and Cold Rolling Mill enables achievement of ±0,025mm thickness tolerance, which is imperative to ease diaphragm spring assemble and applied loads, thus leading to better fatigue results.

CRC samples have shown homogeneous microstructure formed by ferrite matrix and scattered carbides (Figure 9), cementite and vanadium enriched carbides.



(a)

(b)

Figure 9. Micrographs of Cold Rolled sample, (a) 1000x and (b) 6500x. SEM – SE – Nital 2%.

The two very distinct microstructures observed on HRC (Figure 7) and CRC (Figure 9) samples, as expected, have generated very different tensile test results (Table 2). Its easily observed an approximately 50% reduction in Yield Stress (YS) and Tensile Stress (TS) and a 150% increase in elongation (El50).

Table 2. Tensile tests results BW BL 50CrV4

Sample	YS (MPa)	TS (MPa)	El50 (%)
HRC	834	1097	10
CRC	435	549	25

3.4 Diaphragm Spring Production

CRCs were shipped to Clutch producer (Figure 4). Firstly the strip is cut into diaphragm spring blank in 4 steps, including edge smoothing at stress relief hole. Then the blank is heated in a continuous roller furnace to 900°C and then pressed into shape whilst cooled to 40°C in oil. The entire press hardening process took less than 3 min. Subsequently the spring is tempered at 450°C for 1 h. An additional induction heating followed by air quenching is performed only at the inner portion of the release lever (Figure 10). This process is necessary to increase hardness at the spring portion that is wear stressed by clutch moving parts. Afterwards the whole spring goes under shot peening to introduce compression stress to further increase fatigue strength of the part.

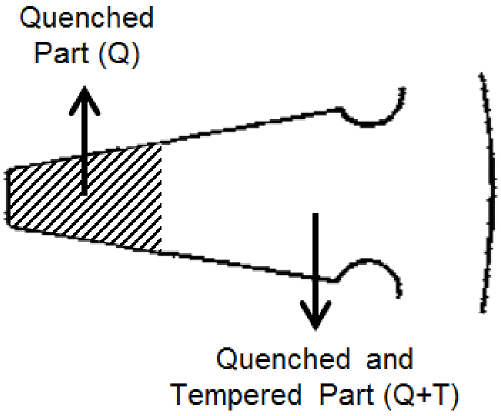
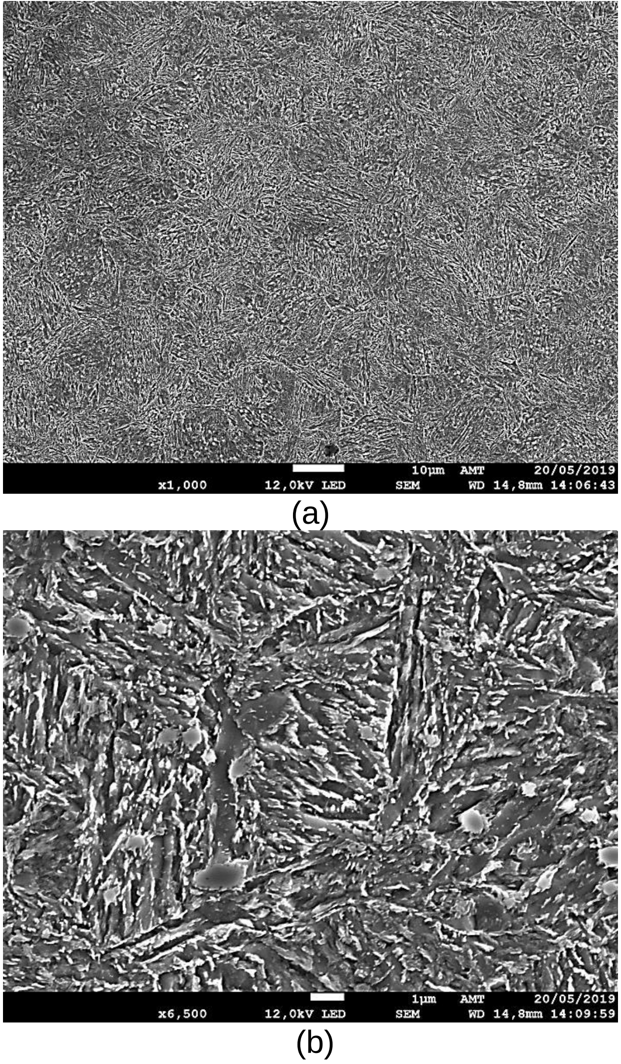


Figure 10. Section of diaphragm spring showing differential heat treatment regions.

The outer portion of the spring (Q+T) showed fully martensitic microstructure (Figure 11), whilst the inner portion (Q) of the spring presented apparently more refined martensite associated with scattered carbides precipitation (Figure 12)

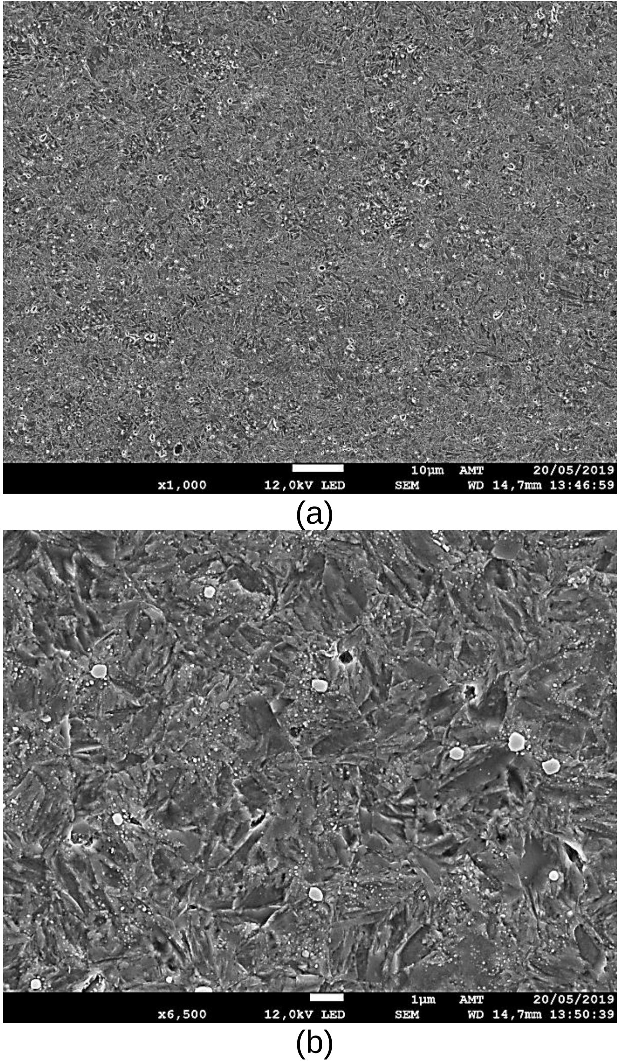
Rockwell C and B hardness tests were performed on HRC and CRC samples, respectively. To avoid shot peening interference, Vickers micro hardness measurements were taken in the middle of the thickness in both Q and Q+T portions of the spring. The results were converted to Vickers to be compared (Figure 13).



(a)

(b)

Figure 11. Micrographs of Diaphragm Spring sample, Q+T region, (a) 1000x and (b) 6500x. SEM – SE – Nital 2%.



(a)

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Figure 12. Micrographs of Diaphragm Spring sample, Q region, (a) 1000x and (b) 6500x. SEM – SE – Nital 2%.

Median results of HRC (354 HV) and CRC (192,5 HV) samples corroborate tensile tests results (Table 2) and observed microstructure, bainite+degenerated perlite +ferrite and ferrite+scattered carbides, respectively. Q+T region revealed median result (401 HV) higher than HRC but lower than Q region (707,5 HV). This difference is also explained by the microstructures found in HRC, Q+T and T samples: ferrite+ degenerated perlite+ferrite, tempered martensite and martensite+scattered carbides, respectively. Spring results (Q and Q+T) have displayed wider spread than HRC and CRC samples, probably associated to greater sensibility of micro Vickers. Even greater spread in Q sample could be explained by carbides density.

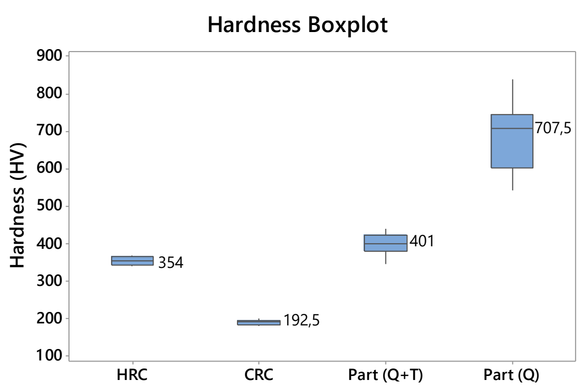

Figure 13. Hardness Boxplot for BW BL 50CrV4 tested samples.

As exposed in this paper, the production of diaphragm spring with BW BL 50CrV4 is very complex and has several key details along the process to be successful.

4 CONCLUSIONS

- Tight control of steel refining and casting parameters is vital to have a very good cleanliness.
- Work window of Hot Rolling process is very restrict to attain both good microstructure and mitigate grain boundary oxidation.
- Diaphragm spring differential heat treatment is important to grant adequate mechanical properties to each part of the spring.
- Microstructural control is utterly necessary throughout the entire process to improve steel performance both in the subsequent process and in the end use.
- BW BL 50CrV4 fulfills all critical metallurgical characteristics and quality requirements to produce diaphragm springs.

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