Strategic approaches to enhance quenching and partitioning applicability: optimizing mechanical properties and microstructure of commercial low-silicon 20MnB5 steel

M. Belfi, T. Carrara, S. Barella, A. Gruttadauria, P. Cetto

Quenching and partitioning (QP) is a heat treatment designed to induce a multiphase microstructure composed of martensite and retained austenite. This treatment introduces high tensile properties in the material, coupled with enhanced ductility compared to traditional treatments. This enhancement arises from the strain-induced transformation of retained austenite into martensite when subjected to loads. Austenite stabilization at room temperature is achieved through carbon diffusion from martensite to austenite during partitioning. Therefore, the chemical composition of the alloy is typically tailored to promote this phenomenon. Silicon is added to suppress carbide precipitation, while manganese is added to enhance austenite stability. However, in this study, we focus on commercial low-silicon 20MnB5 steel. This grade is a low-alloyed steel commonly used in the heat-treated condition and is potentially influenced by the properties introduced through QP treatment. Multiple quenching and partitioning treatments are designed and executed to investigate the applicability of QP on 20MnB5 steel. Intercritical treatment strategies are employed to enhance the hardenability of the selected alloy, aiming to prevent bainite transformation and increase the effectiveness of quenching and partitioning, increasing the free carbon at disposal for partitioning. XRD analyses are conducted to identify retained austenite in the final specimen, quantify its amount, and observe its morphology and location. Optical microscopy (OM) and scanning electron microscopy (SEM) are used to characterize the introduced multiphase microstructure. Tensile tests are performed to assess the mechanical properties introduced by the treatment. In conclusion, the study demonstrates the applicability of intercritical quenching and partitioning (QP) treatments on 20MnB5 steel. However, in the observed conditions, the stabilization of a fraction of retained austenite is not correlated to the greatest increase in UE, leading to the conclusion that the control of the surrounding microstructure is the primary factor that influences the final properties of the material.

KEYWORDS: QUENCHING AND PARTITIONING, MULTIPHASE STEEL, LOW-SILICON STEEL, TENSILE PROPERTIES, HARDENING COEFFICIENTS

INTRODUCTION

In 2003, Speer et al. introduced Quenching and Partitioning (QP), a heat treatment method aimed at achieving a microstructure consisting of martensite and retained austenite (RA) [1]. The presence of this soft phase within the microstructure not only increases ductility and especially uniform elongation (UE), but also confers high mechanical properties; when subjected to a load, it undergoes a strain-induced transformation into martensite (known also as TRIP effect), resulting in high ultimate tensile strength (UTS), and higher work hardening at higher strains [2][3]. QP steels are part of

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the 3rd generation AHSS, and they are renowned for their exceptional blend of strength, toughness, and formability [4]. The outcome is indeed a steel possessing high strength, favorable ductility, and enhanced formability, rendering it suitable for automotive applications such as body panels and structural components. The chemical composition of QP steels is usually tailored in order to maximize the effectiveness of the treatment. A silicon amount (>1 %wt.) is usually added in order to delay carbide formation increasing the amount of free carbon available for partitioning, while manganese is added to increase hardenability and help austenite stabilization [5] [6].

However, little work has been done on commercial steel grades, while most of the research has focused on laboratory composition. 20MnB5 is a commercial low-carbon boron steel used in applications where good strength is required, such as gears and axles. The application of QP is investigated because of the set of properties that is introduced by the treatment. In addition to the design and the application of the treatment, a new challenge is faced, as the low amount of alloying elements reduces the hardenability of the material: the cooling rate given by salt baths indeed is not enough to avoid phase transformation during quenching, leading to an uncontrolled microstructure. The generation of bainite during cooling can reduce the amount of free carbon at disposal for partitioning, reducing the effectiveness of the treatment. As a consequence, a different strategy based on the introduction of multiphase microstructures through intercritical treatments is implemented [7]. Microstructure and tensile properties introduced are characterized, with special focus on the differences in the work hardening of the material.

MATERIALS AND METHODS

The composition of the studied 20MnB5 steel, measured with a Bruker Q4 Tasman quantometer is reported.

Tab.1 - 20MnB5 chemical composition.

Element	C	Si	Mn	Cr	B	P	S	Fe
Wt.%	0,20	0,28	1,21	0,23	0,0027	0,008	0,01	Balance

Critical temperatures A1 (696 °C), A3 (810 °C) were computed through Thermocalc 2022b. Quenching and partitioning treatments have been performed using muffle ovens and salt baths, after a normalization at 850 °C. The process parameters for the heat treatments are reported in Table 2 and Table 3 for the intercritical case and the continuous cooling case respectively.

Tab.2 - Intercritical quenching and partitioning treatments.

Specimen	Aust	Ti [°C]	t_i [min]	T_q [°C]	t_p [min]
770	850 °C, 5 min	770	5	240	10
780	850 °C, 5 min	780	5	255	10
790	850 °C, 5 min	790	5	270	10

Tab.3 - Continuous cooling (CC) + tempering quenching and partitioning treatments.

Specimen	Aust + Intercritical	TQ_1 [°C]	T_t [°C]	t_t [min]
770-CC	850 °C, 5 min + 770 °C, 5 min	190	240	10
780-CC	850 °C, 5 min + 780 °C, 5 min	200	255	10
790-CC	850 °C, 5 min + 790 °C, 5 min	210	270	10

Quenching temperatures were optimized applying the constrained carbon equilibrium (CCE) to the carbon-enriched austenite, and corrected following the 85%-15% rule proposed by Santofimia et al. [8] to decrease the amount of fresh martensite formed during the second quenching phase.

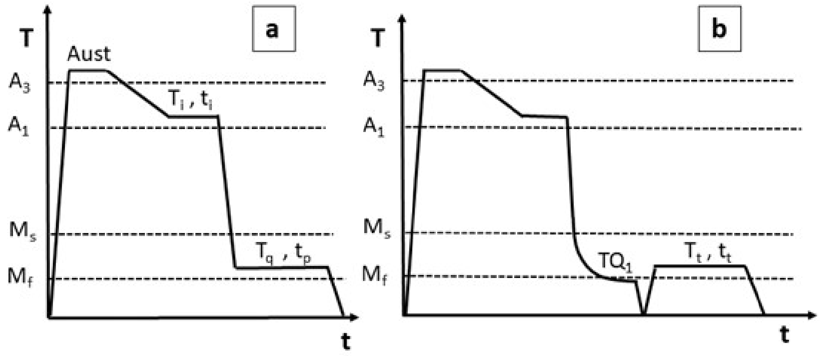


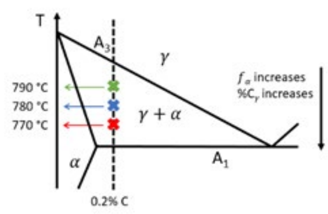
Fig.1 - QP treatments. a) Intercritical treatment, b) Continuous cooling partitioning + tempering.

XRD analyses were performed through a Rigaku SmartLab SE using a D/Tex Ultra 250 1D as a detector. X-ray worked at 40kV and 40 mA, with a Cu Kβ source. Scan range went from 35° to 120° with step size of 0,02° and a scan speed of 1°/min. Rietveld analysis was performed on the integrated software Smartlab Studio II. A Carl Zeiss EVO 50 equipped with FEG was used for SEM analyses. Samples were etched with Nital 2%. Tensile tests were conducted on cylindrical samples, following the standard ASTM E8-M, with a MTS100 machine, with 2 mm/min crosshead speed and initial gauge length of 50 mm. One sample per each condition was tested.

RESULTS

The intercritical approach is employed to control the microstructural evolution during cooling in order to avoid bainitic transformation and to achieve partitioning of carbon in retained austenite. Different QP treatments are designed starting from temperatures between the critical points A1 and A3. In this zone (γ+α), both α ferrite and γ austenite are stable, and due to low carbon solubility in ferrite, austenite is enriched in carbon, displacing CCT curves for longer times and increasing the amount of free carbon at disposal for partitioning. However, the amount of initial austenite should be high enough to ensure the stabilization of a sufficient amount of retained austenite at room temperature. Consequently, three different intermediate temperatures between A1 and A3 are selected to explore different starting fractions of austenite and ferrite (fγ and fα respectively) with different carbon contents (presented in Table 4).

Tab.4 - Austenite and ferrite theoretical fractions and carbon concentrations in the intercritical region.

Specimen	fα (%)	fγ (%)	%Cγ	Ms [°C]	Mf [°C]	
770	43	57	0,33	335	221	
780	35	65	0,30	348	239	
790	27	73	0,27	359	254	

SEM and OM images show that a multi-phase microstructure was introduced in the different samples. A fraction of ferrite is present in the different samples. Sample 790 shows an increased amount of bainite with respect to the other cases. This is consistent with the initial lower carbon concentration in austenite, which has led to more intense phase transformation during the cooling phase.

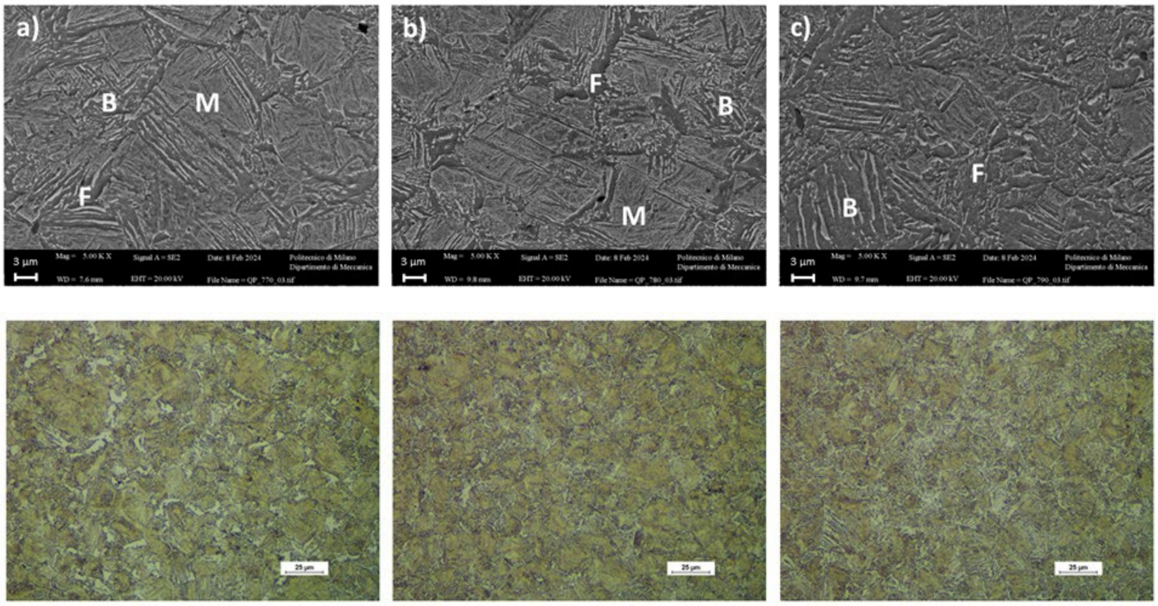


Fig.2 - SEM an OM images for the intercritical samples: a) 770, b) 780, c) 790.

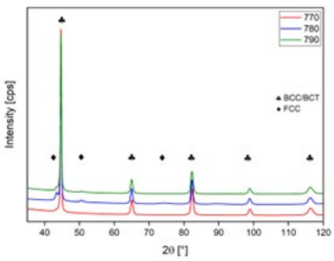
	Specimen	RA %
	770	-
	780	9
	790	3

Fig.3 - X-Ray diffraction spectra for intercritical samples.

X-ray diffraction shows the presence of RA in the 780 and 790 sample, while no RA is detected in sample 770. Tensile properties are presented in Figure 4 and Table 5.

Tab.5 - Tensile properties for the intercritical treatment. The asterisk refers to samples broken outside the gauge length.

Specimen	YS [MPa]	UTS [MPa]	A%	UE %
770	554	910	18	6,7
780	572	886	*	5,8
790	599	882	20	7,0

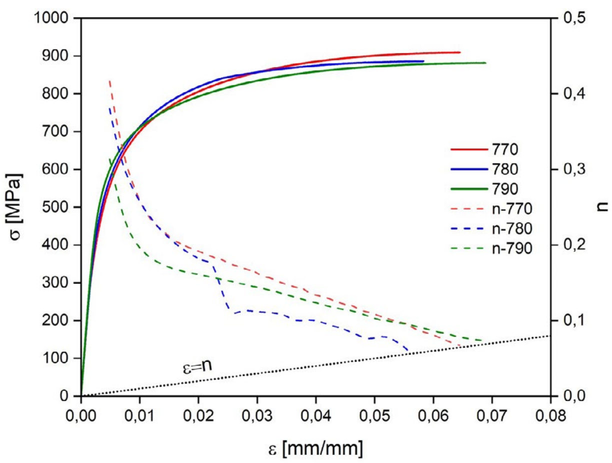


Fig.4 - Tensile properties and hardening coefficient evolution for the intercritical samples

Although the samples show similar tensile properties, the hardening coefficients show different behavior. Initial hardening coefficient is lower in sample 790, which features the lowest amount of martensite. The presence of ferrite keeps a high n for higher strains. The presence of retained austenite (sample 780-790) enhances for higher strains. Sample 780 especially, shows the most intense TRIP effect and a two stage hardening [2][3]. However, this sample is not featuring the highest UE, leading to the conclusion that, in multiphase conditions, RA presence is not always the key leading factor for improving ductility. As an example, sample 790, which has lower amount of RA shows improved UE as well as YS.

A continuous cooling approach (shown in Figure 1b) was used to exploit auto-tempering during cooling between Ms and Mf to stabilize an austenite fraction. The salt bath was placed at a temperature just below Mf to slow the last stages of cooling, in an area where, given the low amount of austenite not yet transformed, carbon diffusion could stabilize a fraction of it. As the holding time is very low, following the final quenching step, a 10 minutes tempering stage at the optimal partitioning temperature (from CCE) is applied to enhance ductility of martensite. The microstructures obtained through continuous cooling strategy are shown in Figure 5. Sample 770-CC, 780-CC and 790-CC show respectively a ferritic-martensitic, ferritic-bainitic-martensitic and bainitic-martensitic microstructure. Coherently with the designed treatment, the higher the amount of ferrite, the higher the carbon content in austenite and thus its hardenability.

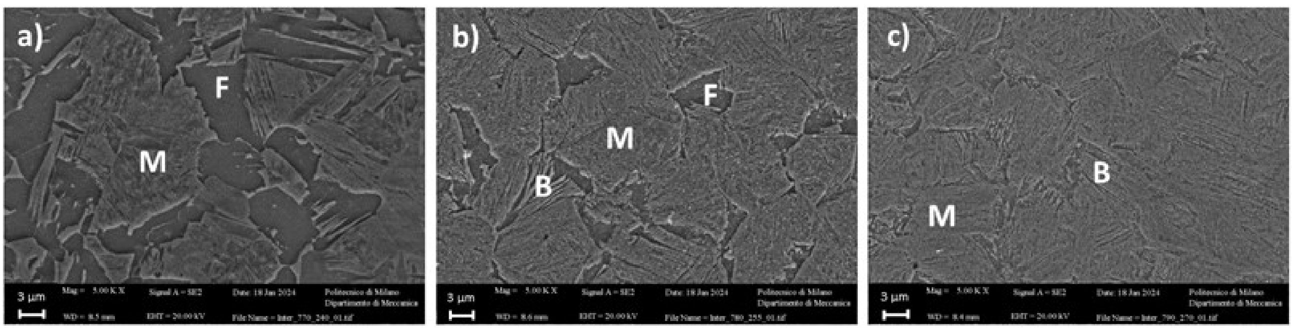


Fig.5 - SEM pictures for samples: a) 770-CC, b) 780-CC, c) 790-CC.

Tab.6 - X-Ray diffraction results.

Specimen	RA%
770-CC	-
780-CC	2
790-CC	2

The amount of RA introduced in this case is lower than the one observed in the intercritical treatment, as the amount of time for partitioning during continuous cooling is lower than the for intercritical treatments.

The tensile properties of the continuous cooling strategy samples are shown in Table 7. Yield strength decreases with increasing amount of soft ferrite in the microstructure, coherently with the rule of mixtures. Good combination of tensile properties and elongation is observed in all the different cases.

Tab.7 - Tensile properties for continuous cooling samples.

Specimen	YS [MPa]	UTS [MPa]	A%	UE %
770-CC	709	1057	17	5,07
780-CC	779	1010	*	4,48
790-CC	857	1119	*	4,03

Hardening coefficients are correlated with the microstructural features of the material. Due to its increased hardening coefficient, the presence of ferrite increases the overall hardening coefficient of the material for higher strains. Samples 780-CC and 790-CC, feature a two stage hardening, linked to the occurrence of strain induced transformation. 770-CC case, containing ferrite and tempered martensite, shows the greatest hardenability.

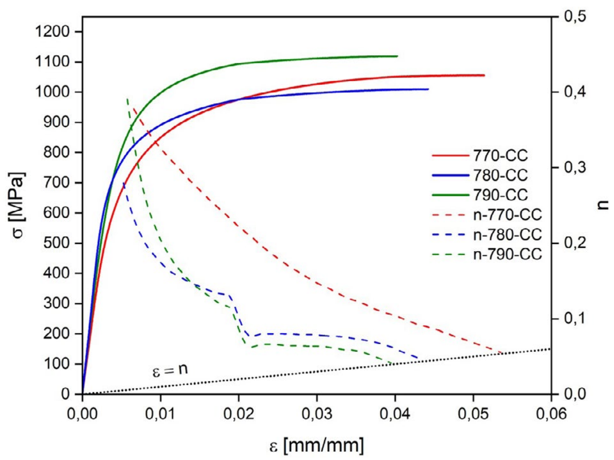


Fig.6 - Tensile tests and hardening behavior of CC samples.

DISCUSSION

The effectiveness of QP depends largely on its ability to control the diffusion of carbon within the austenite, preventing competitive phenomena that trap it. Silicon for example is added to slow the precipitation of carbides [5]. The formation of bainite (α + Fe_3C) should consequently also be avoided as far as possible. However, the chemical composition of 20MnB5 does not allow a martensitic microstructure to be obtained during quenching in the salt bath. The development of intercritical treatments attempts to address these issues through the creation of a multiphase, controlled microstructure that promotes treatment efficacy. Partial austenitization in the $\gamma + \alpha$ range leads to increased carbon concentration in the austenite, retarding the transformations during cooling. The initial fraction of the two phases should be chosen carefully: too high a percentage of ferrite can lead to an insufficient final amount of martensite, from which carbon diffusion can start, leading to a modest amount of retained austenite. This corresponds to case 770. A too high amount of low-carbon austenite instead is not able to avoid transformations during cooling (case 790). The tensile properties introduced by these treatments are found to be high, and a fraction of retained austenite has been introduced in 780 and 790 samples, showing the effectiveness of this approach. The differences in work hardening coefficients show that different microstructural conditions were obtained. 790 case shows the lowest starting hardening coefficient, because of its lower martensitic and higher bainitic fraction [9][10]. The presence of RA increases n for higher strains in 780 and 790 case, while the hardenability of 770 case is given by the presence of ferrite [2][3]. Unsuspiciously, 780 case (with highest RA), is not the one with the highest UE, while the best case turns out to be 790, where a lower fraction of retained austenite is obtained, but overall a better uniform elongation as well as YS is obtained.

CC treatments show excellent mechanical properties but lower UEs. Yield strength varies with the amount of ferrite present in the microstructure, and a fraction of retained austenite is observed in the 780-CC and 790-CC cases. it is interesting to observe that in the 770-CC case (without RA), the work hardening coefficient is high even at high strains due to the presence of ferrite, and that it is also higher than the 780-CC and 790-CC cases that show the occurrence of TRIP effect.

Both the intercritical and the continuous cooling approach result effective in ensuring the stabilization of RA through quenching and partitioning in 20MnB5 steel. However, these results lead to the conclusion that in the obtained complex multiphase microstructures, stabilization of a fraction of retained austenite is not the primary way to enhance the strength and ductility of the material. The features of the multiphase matrix (phases and quantities) turn out to be the crucial point for controlling the final material properties.

CONCLUSIONS

Two strategies, namely intercritical treatment and continuous cooling and tempering, were employed to enhance the applicability of quenching and partitioning on low carbon-low silicon 20MnB5 steel. The outcome of the work is presented hereby:

- Intercritical QP treatments introduce multiphase microstructures composed of ferrite, martensite, bainite and retained austenite. High tensile properties (800-900 MPa of UTS) and ductility (18-20%) are obtained.
- Samples 780 and 790 show a fraction of retained austenite stabilized at room temperature. 770 sample, featured by the highest amount of ferrite, shows a dual phase microstructure with no RA.
- Continuously cooled samples show lower amount of retained austenite and higher tensile properties (UTS >1000 MPa) with respect to the previous. Yield strength decreases with ferrite fraction. 790-CC case shows the highest tensile properties.
- A higher uniform elongation is not directly correlated to the occurrence of TRIP effect. Sample 770-CC, composed of a dual phase ferritic-martensitic microstructure, shows the highest hardening coefficient as well as uniform elongation.

The overall behavior of the created microstructures is due to the combination of the effects of the phases within them. As observed in the specimens, the stabilization of a fraction of retained austenite is secondary to the balance of mechanical properties and ductility provided by the other phases present: the TRIP effect does not necessarily provide the greatest increase in UE unless accompanied by control of the entire microstructure.

REFERENCES

[1] J. Speer, D. K. Matlock, B. C. De Cooman, and J. G. Schroth, "Carbon partitioning into austenite after martensite transformation," Acta Mater., vol. 51, no. 9, pp. 2611–2622, 2003, doi: 10.1016/S1359-6454(03)00059-4.

[2] K. O. Findley, J. Hidalgo, R. M. Huizenga, and M. J. Santofimia, "Controlling the work hardening of martensite to increase the strength/ductility balance in quenched and partitioned steels," Mater. Des., vol. 117, pp. 248–256, 2017, doi: 10.1016/j.matdes.2016.12.065.

[3] Z. H. Cai, H. Ding, R. D. K. Misra, and Z. Y. Ying, "Austenite stability and deformation behavior in a cold-rolled transformation-induced plasticity steel with medium manganese content," Acta Mater., vol. 84, pp. 229–236, 2015, doi: 10.1016/j.actamat.2014.10.052.

[4] M. Soleimani, A. Kalhor, and H. Mirzadeh, "Transformation-induced plasticity (TRIP) in advanced steels: A review," Mater. Sci. Eng. A, vol. 795, no. July, 2020, doi: 10.1016/j.msea.2020.140023.

[5] I. Miettunen, S. Ghosh, M. C. Somani, S. Pallaspuro, and J. Kömi, "Competitive mechanisms occurring during quenching and partitioning of three silicon variants of 0.4 wt.% carbon steels," J. Mater. Res. Technol., vol. 11, pp. 1045–1060, 2021, doi: 10.1016/j.jmrt.2021.01.085.

[6] B. Kim, J. Sietsma, and M. J. Santofimia, "The role of silicon in carbon partitioning processes in martensite/austenite microstructures," Mater. Des., vol. 127, no. April, pp. 336–345, 2017, doi: 10.1016/j.matdes.2017.04.080.

[7] S. Barella, M. Belfi, A. Gruttadauria, C. Liu, and Y. Peng, "Metallurgical and Mechanical Investigation on Single-Step Quenching and Partitioning Thermal Treatments on Commercial Low Alloyed 30MnV6 Steel," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., pp. 12–14, 2023, doi: 10.1007/s11661-023-07262-y.

[8] C. Celada-Casero, C. Kwakernaak, J. Sietsma, and M. J. Santofimia, "The influence of the austenite grain size on the microstructural development during quenching and partitioning processing of a low-carbon steel," Mater. Des., vol. 178, 2019, doi: 10.1016/j.matdes.2019.107847.

[9] H. Ashrafi, M. Shamanian, R. Emadi, and N. Saeidi, "Correlation of Tensile Properties and Strain Hardening Behavior with Martensite Volume Fraction in Dual-Phase Steels," Trans. Indian Inst. Met., vol. 70, no. 6, pp. 1575–1584, 2017, doi: 10.1007/s12666-016-0955-z.

[10] M. M. Karimi and S. Kheirandish, "Comparison of work hardening behaviour of ferritic-bainitic and ferritic-martensitic dual phase steels," Steel Res. Int., vol. 80, no. 2, pp. 160–164, 2009, doi: 10.2374/SRI08SP082.

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