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Analysis of the applicability of Quenching and Partitioning treatment on high-strength commercial steels

M. Belfi, S. Barella, A. Gruttadauria, P. Cetto, C. Mapelli

Quenching and Partitioning (QP) is a heat treatment for high-strength steels which aims to introduce at room temperature a microstructure composed of martensite and retained austenite. The presence of these phases provides an enhanced strength-ductility balance which are difficult to achieve with conventional treatments. This treatment is generally applied to steels with specific chemical compositions (QP steels), characterized by a high amount of silicon and manganese, which enhance the effectiveness of the treatment. However, these chemical compositions are far from those usually produced in industry. This study investigates the feasibility of applying QP on several commercial high-strength steels, whose chemistries are not specifically designed for this treatment but are already industrially produced. Criteria for material selection and process parameters are presented, and microstructural features and final mechanical properties are analyzed. The aim of the study, which is based on our previous research, is to provide guidelines for the application of QP on commercial steels, indicating limitations and possibilities.

KEYWORDS: QP, SINGLE-STEP, COMMERCIAL STEEL, AHSS, RETAINED AUSTENITE;

INTRODUCTION

Quenching and Partitioning (QP) is a heat treatment designed to achieve a microstructure composed of martensite and retained austenite (RA), first proposed by Speer et al. in 2003 [1]. The presence of these phases provides a combination of high tensile strength and ductility that cannot be achieved by traditional treatments [2]. The martensitic matrix gives high tensile properties, while the soft RA improves ductility. Moreover, the latter transforms into martensite during loading through a strain-induced transformation, contributing to high tensile properties [3]. The heat treatment consists of an austenitization (seldom partial), followed by an incomplete quenching between M_s and M_f. After this step, an isothermal holding called partitioning is performed either at the same temperature (single step, SS) or at a higher one (double step, DS). During this phase, carbon diffusion from the supersaturated martensite to austenite is promoted: stabilization is obtained when the M_s for austenite is moved below room temperature. Meanwhile, during partitioning, the martensitic matrix is tempered. The tempering of martensite, and the features of retained austenite, namely: amount, stability, morphology, are key factors for controlling the final properties. SS-QP treatments are performed at a lower partitioning temperature with respect

Marco Belfi, Silvia Barella, Andrea Gruttadauria, Pietro Cetto, Carlo Mapelli
Politecnico di Milano, Italy

to DS-QP, thus they feature lower carbon diffusivity which, leading to higher tensile properties but lower ductility, and longer partitioning times are needed to achieve sufficient ductility and martensite tempering. Nevertheless, SS-QP treatments are simpler (fewer process parameters) and potentially more cost-effective because they are performed in a single salt bath kept at lower temperatures (between M_s and M_f). The research presented in this work has focused mainly on SS-QP treatments.

QP steels belong to the 3rd generation of Advanced High-Strength Steels (AHSS) and are known for their exceptional combination of strength, toughness, and formability [4]. This makes them suitable for automotive applications such as body panels and structural components. The chemical composition of QP steels is typically adjusted to maximize the effectiveness of the treatment. Silicon (>1 wt.%) is usually added to suppress or at least delay carbide formation: this is an undesired phenomenon because it reduces the amount of free carbon available for partitioning [5]. Other alloying elements such as manganese or nickel are introduced as they enhance the hardenability and are austenite stabilizers. Most research in literature has focused on laboratory compositions tailored for the treatment rather than commercial steel grades already studied in the industry, which might be interested by the combination of properties introduced by such a treatment [6,7]. The study proposed here is intended to provide a summary of our recent studies on the application of single-step QP treatment on commercial steels. The design, application and analysis on different chemical compositions is presented, with the aim of providing insight into the design parameters of the heat treatment, the mechanical properties introduced, in order to provide an overview of the results obtained and the positive features and limitations of the application of this treatment.

RESULTS

CHEMICAL COMPOSITION

The selection of the material must set the conditions for an effective QP treatment. The steels were selected based on three selection criteria, namely: 1) they must be commercial low-alloyed steels used for high strength applications, 2) have sufficient carbon concentration to achieve martensite formation (%C > 0.2), and 3) have enough alloying elements to guarantee sufficient hardenability during salt bath quenching. The chemical compositions of the selected steels are presented in Table 1.

Tab. 1 - Composizione chimica degli acciai commerciali analizzati nel presente studio – Chemical composition of the analyzed steels.

Wt. %	C	Si	Mn	Cr	Ni	Mo	V	B	Fe
30CrNiMo8	0.30	0.40	0.65	2.0	2.0	0.4	-	-	Bal.
AISI 420	0.25	0.33	0.40	13.5	-	-	-	-	Bal.
AISI 4140	0.41	0.19	0.84	1.15	-	0.18	-	-	Bal.
AISI 4340	0.43	0.25	0.70	0.80	1.8	0.30	-	-	Bal.
33MnCrB5	0.32	0.19	1.27	0.33	-	-	-	0.0025	Bal.
30MnV6	0.28	0.66	1.46	0.18	-	-	0.11	-	Bal.
20MnB5	0.20	0.28	1.21	0.23	-	-	-	0.0027	Bal.
C35	0.35	0.23	0.63	-	0.16	-	-	-	Bal.
C45	0.47	0.22	0.70	0.18	-	-	-	-	Bal.

In Fig. 1, the chemical composition of the selected alloys compared with a pool of compositions found in literature is presented. The focus is set especially on C-Si (Fig. 1a) and Si-Mn (Fig. 1b) contents since these elements were identified as the most relevant in QP steels. The chosen low-alloyed commercial compositions are generally characterized by a lower percentage of Mn and Si than the QP steels studied in the literature, as the levels used in literature still cause production issues in industrial settings. However, the low presence of silicon (<1%) does not allow control of carbide precipitation during partitioning [5]. The low amount of manganese in the alloy also decreases the hardenability. As a result, a higher amount of carbon is required to compensate for these two shortages. Hardenability was indeed identified as the most constraining factor, as the cooling rate obtained during salt bath quenching was not enough to avoid further phase transformation in C35, C45 and 20MnB5 steels: these compositions, which are represented with a red-dot in Fig. 1, are consequently considered as a lower bound limit for the chemical composition for QP application.

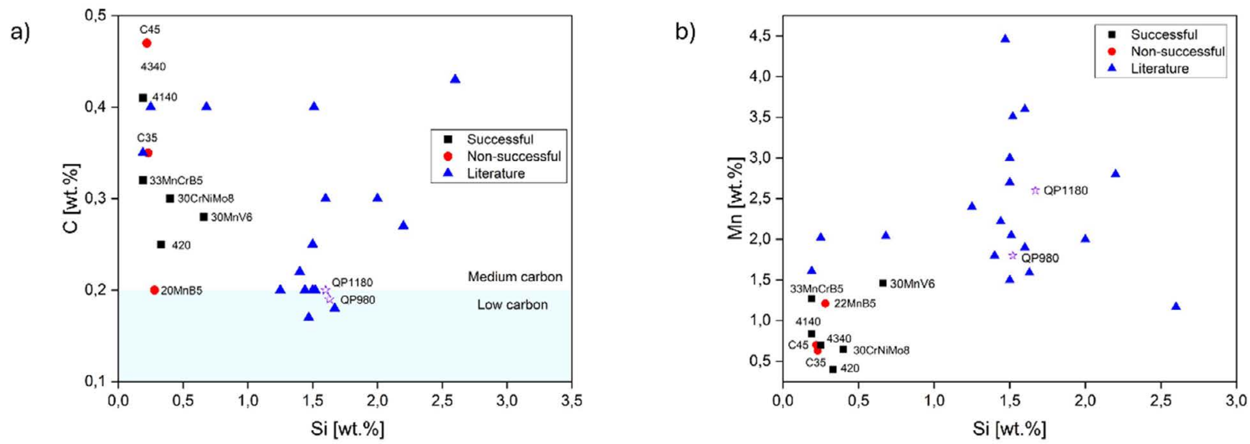
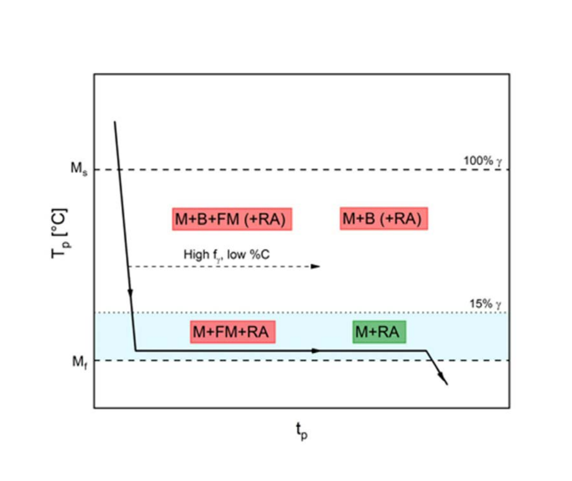


Fig.1 - Confronto tra le composizioni chimiche degli acciai commerciali scelti nel presente studio (nero, rosso) e gli acciai tratti dalla letteratura (blu) [2,5,8-21]. a) C-Mn, b) Mn-Si / Chemical composition comparison between the low-alloyed commercial compositions selected in the present study (black, red) and the steels found in multiple work in literature (blue)[2,5,8–21]. a) C-Mn, b) Mn-Si

The selection of the process parameters is crucial to introduce the desired microstructure at room temperature. The quenching temperature T_q (T_p=T_q in single-step treatments) must be selected to obtain the correct amount of RA after the first quenching phase: A high T_q leads to a low martensite fraction and free carbon and thus can lead to insufficient austenite stabilization and consequently to fresh martensite (FM) formation. Fresh martensite formation must be avoided as far as possible because its brittleness reduces the mechanical properties of the alloy [16]. Moreover, a high T_q can set the conditions for isothermal bainitic transformation of austenite and carbide precipitation [22][23]. A low T_q instead can lead to an insufficient RA amount. Although Constrained Carbon Equilibrium (CCE) identifies an optimal T_q, its results are often overestimated because of the difference between the real conditions and the hypothesis of the model, namely: full partitioning, no carbide formation and fixed interface. Consequently, Celada-Casero et al. [21] identified as 15-20% the maximum amount of austenite after first quenching to maximize the effectiveness of the treatment: using the CCE model, it is possible to identify the corresponding T_q [1]. Regarding the partitioning time (t_p), if too short, insufficient stabilization of RA is obtained, while excessively long times can lead to isothermal transformation of austenite [23]. The different possible cases are presented in Fig. 2. These constraints lead to a narrow operating window for SS-QP treatments. The best results for the selected steels are obtained when T_q is low and t_p is medium-high (in the order of 10-120 minutes) are presented in Fig. 2.



Material	T_q [°C]	t_p [min]
30CrNiMo8	235	10-120
AISI 4140	240	1-20
AISI 4340	200-220-240	10-30
33MnCrB5	240-260	5-10
30MnV6	220-240	10-20

Fig.2 - Schematizzazione del trattamento di SS-QP e riassunto dei parametri di processo efficaci negli acciai studiati / Schematization of SS-QP treatment and summary of effective process parameters in the studied steels

MICROSTRUCTURAL CHARACTERIZATION

The typical microstructure of a QP-treated steel is presented in Fig. 3. As previously explained, the final microstructure after a SS-QP treatment is ideally composed of a tempered martensite and a fraction of stable RA. Actually, especially for commercial composition, the optimal selection of parameters can be hardly found, leading to the presence of fractions of FM and bainite. EBSD analyses are a powerful tool that can be used to clearly distinguish between phases and to study morphology and distribution of RA in the martensitic matrix.

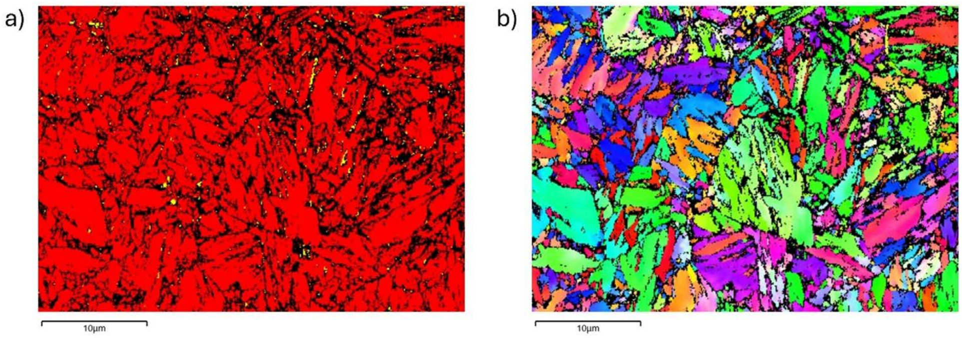
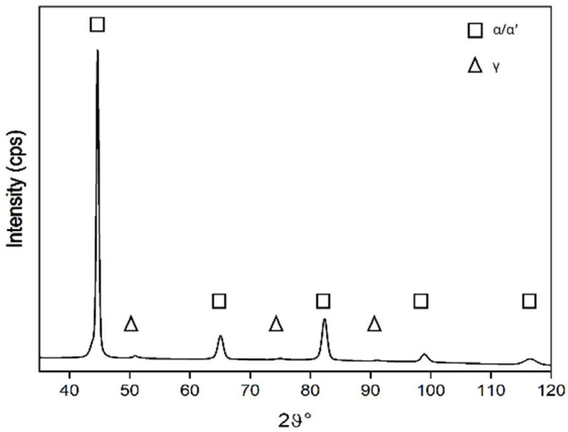


Fig.3 - Analisi EBSD su acciaio 30MnV6 trattato con SS-QP. Austenite in giallo, martensite in rosso. a) Mappa delle fasi, b) IPF / EBSD analysis on SS-QP treated 30MnV6 steel. Austenite in yellow, martensite in red. a) Phase diagram, b) Inverse Pole Figure.

In Fig. 3a, a fraction of thin RA is visible in the martensitic matrix. As SS-QP treatment feature low diffusivity, usually the stabilized thickness of RA is low, and a fine interlath or GB retained austenite is obtained, while blocky retained austenite is less present. The IPF map presented in Fig. 3b shows that the microstructure is homogeneous and non-oriented. It must be clarified that EBSD analyses always show a lower RA fraction than the one measured by XRD, because of the high sensitivity of RA to surface preparation and resolution issues of the machine itself, as literature has observed the nanometric dimension of some RA grains [24]. The RA fractions obtained through X-Ray diffraction for different alloys are presented in Tab. 2 along with a typical XRD spectrum for QP steels.

Tab.2 - Schematizzazione del trattamento di SS-QP e riassunto dei parametri di processo efficaci negli acciai studiati / Schematization of SS-QP treatment and summary of effective process parameters in the studied steels

Material	RA %
30CrNiMo8	5-13
AISI 420	8-11
AISI 4140	4-8
AISI 4340	4-8
33MnCrB5	3-5
30MnV6	4-6



MECHANICAL PROPERTIES

The results of the tensile tests are presented in Fig. 4. The different QP treated steels (full dots) show ultra-high tensile properties, always above 1400 MPa. The comparison between QP and QT (half-full dots) samples shows that similar UTS values are obtained in both conditions, but the QP treated samples feature a higher ductility. A difference is observed regarding the YS (presented in Fig. 4b), which is lower in QP samples compared to the QT counterparts. This effect is due to the presence of soft retained austenite which increases the work hardening also through a decrease in the overall yield strength. However, the comparative QT samples are designed to have a martensite tempering similar to the one given by QP through a tempering treatment performed at T_q, t_p and its final tensile properties are not representative of practical applications. Therefore, these samples serve to isolate and highlight the contribution of RA to tensile behaviorThe ultra-high tensile properties shown make QP samples usually compliant to both standards regarding both the UTS and A%. Compared to QP1180 steel, higher UTS and YS are obtained, but with similar A% (especially for 30MnV6 and 33MnCrB5).

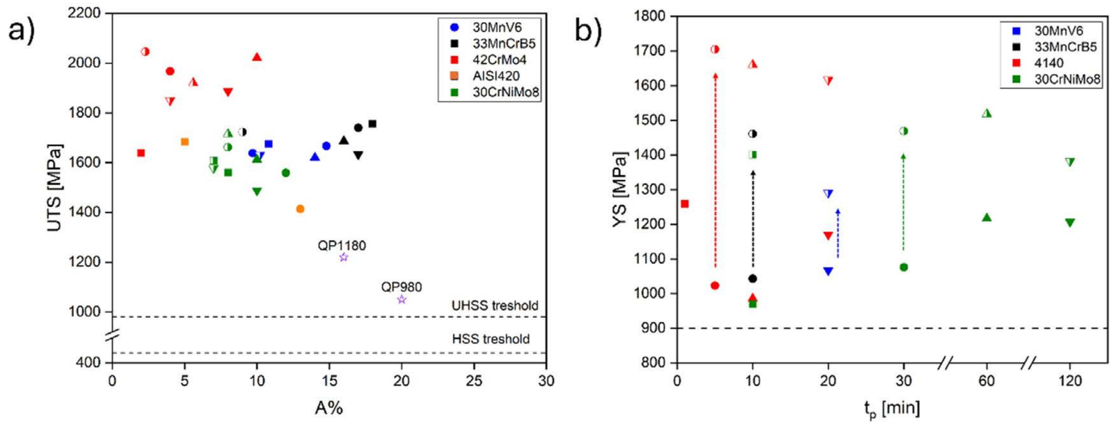


Fig.4 - Proprietà tensili degli acciai trattati. I simboli pieni corrispondono ai campioni QP. Ogni punto si riferisce al valor medio di diverse prove di trazioni. I simboli pieni a metà si riferiscono a campioni QT comparativi con la stessa t_p. Le stelle viola si riferiscono a quelle degli acciai QP980 e QP1180. / *Tensile curves of the heat-treated steels. Solid symbols correspond to QP samples. Each point represents the average result of multiple tensile tests. Half-filled symbols refer to comparative QT samples with the same t_p. Purple stars refer to properties required by QP980 and QP1180 steels.*

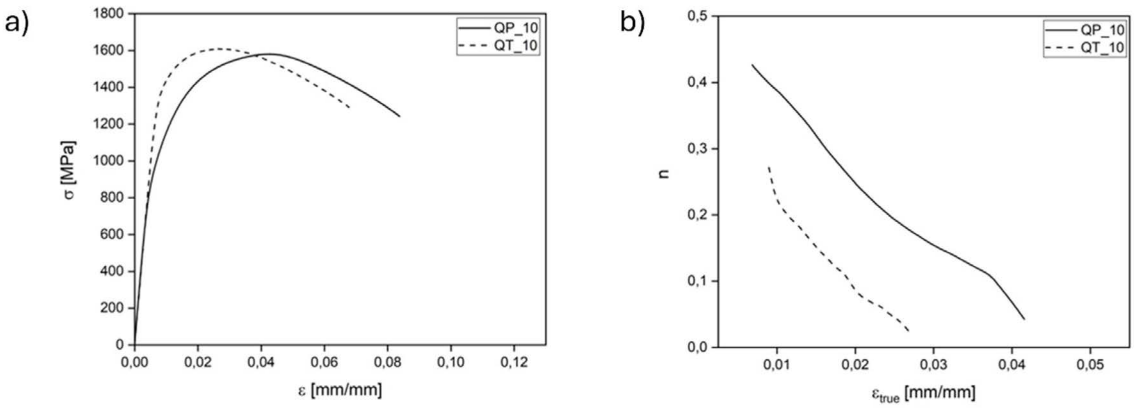


Fig.5 - Confronto tra le prove di trazione QT-QP per l'acciaio 30CrNiMo8 partizionato/temprato a 235 °C per 10 minuti. a) Prove di trazione, b) coefficienti di incrudimento istantaneo / *QT-QP tensile tests comparison for 30CrNiMo8 steel partitioned/tempered at 235 °C, 10 minutes. a) Tensile tests, b) instantaneous hardening coefficients.*

In Fig. 4a, comparative QT and QP samples for a 30CrNiMo8 steel are presented. The two conditions show a similar UTS, as expected by the presence of a same-tempered martensitic matrix. Yield strength is lower in the QP sample, leading to an increased UTS/YS ratio and improved work hardening. The comparative work-hardening behavior of QT and QP is highlighted in Fig. 4b. The trend of the instantaneous hardening coefficient "n" reflects the previous considerations as QP sample shows an increased initial value along straining, leading to an increased uniform elongation (UE). This behavior has been previously observed, and is due to the progressive deformation and transformation of austenite in martensite along straining, which enhances the hardening coefficient delaying the onset of necking [13][25] and so increases ductility and especially uniform elongation.

IMPACT TOUGHNESS AND FRACTURE TOUGHNESS

In addition to tensile properties, steel must guarantee sufficient toughness before being put into service. In the presence of a crack, the material dissipates strain energy through plasticization at the crack tip or through crack propagation. The presence of soft RA in the microstructure is reported to enhance the fracture toughness of steels thanks to its ability to dissipate energy through deformation and strain-induced transformation [26][27]. Toughness can be a major issue for SS-QP treated material, as one of the limitations of the SS-QP treatment is the thin window of process parameters that can be exploited. The use of low temperatures for the treatment allows limited martensite tempering, which can lead to interesting tensile properties but an overall brittle behavior at fracture, even in presence of retained austenite. Some preliminary results are presented in Fig. 6. In Fig. 6a, Charpy samples show an improved toughness for QP samples. Fig. 6b shows the results of fracture toughness tests. In Fig. 6b, the comparison between QT and QP samples shows an improvement in toughness of the latter thanks to RA presence.

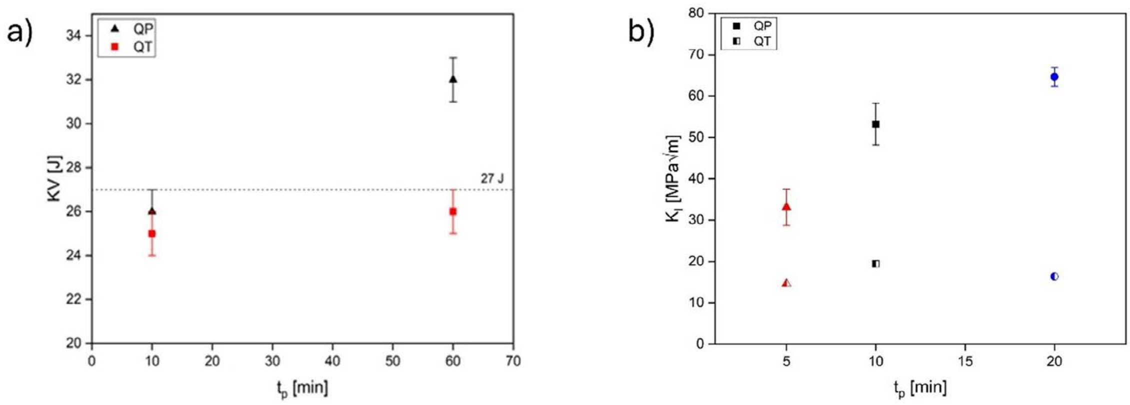


Fig.6 - Confronto tra i valori di resilienza e tenacità alla frattura QT/QP. a) Risultati Charpy KV per un acciaio 30CrNiMo8 partizionato/temprato a 235 °C, b) Risultati della tenacità alla frattura per l'acciaio AISI 4140 / *Toughness values QT/QP comparison. a) Charpy V-Notch results for a 30CrNiMo8 steel tempered/partitioned at 235 °C, b) Fracture toughness results for AISI 4140 steel.*

DISCUSSION

The results of different studies have shown the applicability of SS-QP on commercial steels. The selection of the chemical composition must guarantee the hardenability of the material through salt bath quenching, avoiding other phase transformations. Consequently, compositions such as C35 and 20MnB5 are identified as lower bound for the application of the treatment. Although commercial steels are characterized by a lower amount of Si-Mn compared to tailored QP compositions (Fig. 1) and they feature a reduced efficiency of the treatment due to uncontrolled carbide formation, RA fractions have been successfully stabilized in multiple low-alloyed steel grades. However, although RA contributes positively to ductility and toughness through the TRIP effect, its beneficial impact may not fully compensate for the brittleness of the low-tempered martensitic matrix — especially in SS-QP conditions where partitioning temperatures are limited. Therefore, the overall mechanical balance depends strongly on both RA stability and the extent of martensite tempering.

SS-QP treatments appear to be a promising solution to achieve ultra-high tensile properties coupled with improved ductility compared to traditional treatments. The selection of the parameters for the heat treatment (T_q, t_p) is crucial for achieving the desired final microstructure while avoiding undesired phase transformations, such as bainite and fresh martensite formation [28]. The combination of low quenching temperatures (15% austenite) and medium partitioning times (10-120 minutes) was identified as the most effective.

The computation of the tempering parameter $T(C+\log_{10}t)$ summarizes the time and temperature effect for different tempering treatments, which were individually optimized for the specific steel [29]. This tempering parameter allows for the comparison of different tempering/partitioning treatments and can be used to estimate the thermal energy required in the process; a higher value corresponds to a higher energy consumption (and thus energetic cost) during the treatment. The results summarized in Fig. 7 show the possibility of obtaining comparative YS between QP samples and traditional QT standards, suggesting potential for energy savings and improved ductility at equivalent strength levels.

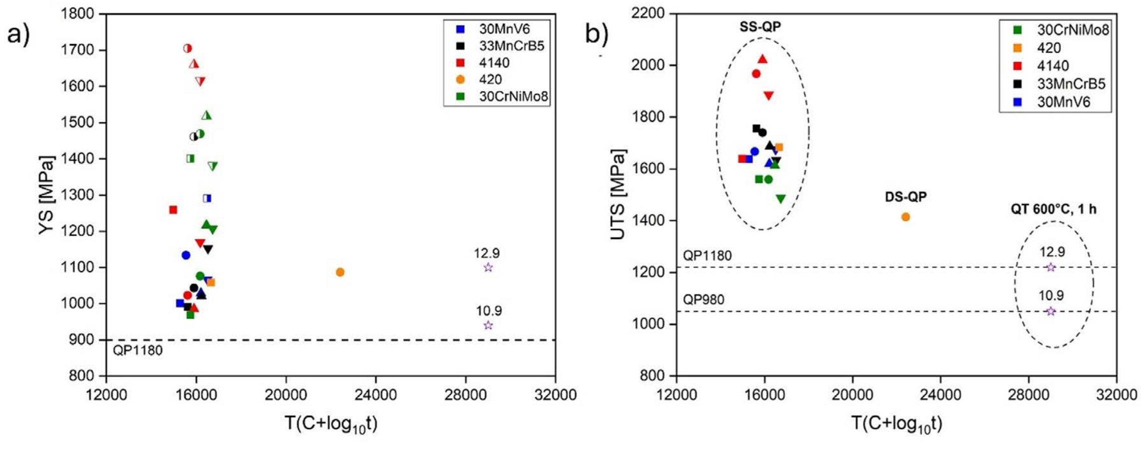


Fig.7 - Rappresentazione delle proprietà meccaniche ottenute con QP (e QT comparativi) in funzione del livello di rinvenimento equivalente. a) Carico di snervamento, b) Carico massimo / *Representation of mechanical properties obtained with QP (and comparative QT) as a function of equivalent tempering level. a) Yield strength, b) UTS*

Compared to their QT counterparts with the same martensite tempering, higher ductility and work-hardening coefficient are obtained in QP conditions, at the expense of decreased YS: these features are due to the progressive deformation and strain induced transformation of RA in martensite during straining. However, even though the presence of soft austenite in QP-treated materials increases the toughness of the material compared to QT conditions, the presence of a low-tempered martensite might lead to an overall brittle behavior which is not acceptable in practical use. A correct combination of martensite tempering and austenite presence can lead to sufficient final toughness, with values similar to more traditional QT treatments (Fig. 6b). In the state of the art, this is one of the major limitations of SS-QP treatment. The variability in the choice of process parameters around the optimum with good results is limited: T_q (equal to T_p) can be neither too high nor too low, and the partitioning time has an upper limit set by industrial common sense and a lower limit due to issues of martensite brittleness. The maximum reachable austenite stability is ultimately low [30]. These constraints limit variability of results that can be obtained as to UTS and RA% from a single chemical composition. Consequently, even if the applicability of SS-QP treatment on commercial steels is assessed, the selection of the composition of the steel should be selected based on the requested final tensile properties taking into account the narrow operating window around the optimal heat treatment. The use of a DS-QP treatment could increase martensite tempering and austenite stabilization thanks to the higher T_p which can be selected independently of T_q, leading to a final material with lower UTS compared to SS-QP condition, but with overall improved toughness. However, the industrial implementation of a DS-QP treatment can be complex due to the presence of two isothermal baths and the increase in the number of process parameters.

CONCLUSIONS

The analysis of the results of the application of SS-QP treatment on a pool of low-alloyed commercial steels was presented. Although the non-tailored composition sets some challenges for the success of the heat treatment and thus must be selected carefully, SS-QP applicability has been assessed on multiple steel grades. Microstructures composed of martensite and RA with ultra-high tensile properties (UTS > 1400 MPa) and improved ductility (reaching also 18%) and toughness were obtained. The selection of low partitioning temperature and medium partitioning times is the most effective for controlling the microstructure. Nevertheless, the main limitation of the treatment is the limited range of effective process parameters around the optimum (especially T_p) for a successful result. The low partitioning temperatures restrict the tempering of the martensitic matrix and carbon diffusion; consequently, even if improved, ductility and toughness remain limited. In conclusion, SS-QP appears to be a promising heat treatment for specific ultra-high-strength applications that require increased ductility and work hardening.

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Analisi sull'applicabilità del trattamento di Quenching and Partitioning su acciai commerciali ad alta resistenza

Il Quenching and Partitioning (QP) è un trattamento termico per acciai ad alta resistenza che permette di avere, a temperatura ambiente, una microstruttura formata da martensite e austenite residua. La presenza di queste fasi conferisce una combinazione di resistenza meccanica e duttilità che è difficilmente ottenibile con trattamenti tradizionali. Questo trattamento è generalmente applicato ad acciai con specifiche composizioni chimiche (acciai QP), caratterizzate da un'elevata presenza di silicio e manganese, che favoriscono l'efficacia del trattamento. Tuttavia, queste composizioni sono lontane da quelle abitualmente prodotte a livello industriale. Il presente studio analizza l'applicabilità del QP su diversi acciai commerciali ad alta resistenza, le cui composizioni chimiche non sono studiate appositamente per questo trattamento, ma sono comunemente già in produzione. Sono presentati criteri per la scelta del materiale e dei parametri di processo, e sono analizzate le caratteristiche microstrutturali e le proprietà meccaniche finali. L'obiettivo dello studio è di fornire, a partire dai risultati di ricerche precedenti, delle linee guida per l'applicazione del QP su acciai commerciali, indicandone limitazioni e possibilità.

PAROLE CHIAVE: QP, ACCIAI COMMERCIALI, AHSS, AUSTENITE RESIDUA;

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