Quenching and partitioning heat treatment: the third generation of advanced high-strength steel

Tratamento térmico de têmpera e partição: terceira geração dos aços avançados de alta resistência

Tratamiento térmico de temple y partición: tercera generación de aceros avanzados de alta resistencia

Renata Neves Penha
ORCID: https://orcid.org/0000-0002-7674-2460
Federal University of Itajubá, Brazil
E-mail: rnp@unifei.edu.br
Yago Francisco Soares Marins
ORCID: https://orcid.org/0000-0003-1350-135X
Federal University of Itajubá, Brazil
E-mail: yg16fsm@unifei.edu.br

Abstract
This manuscript aims to present an overview of quenching and partitioning (Q&P) heat treatment usually applied to transformation-induced plasticity (TRIP) and duplex steels (DP). TRIP and DP are the first generations of advanced high-strength steels (AHSS). AHSSs present multiphase microstructures that ensure an advantageous combination of strength and ductility. The Q&P heat treatment process aims to obtain a mixed microstructure with martensite and retained austenite and improve the relation strength/ductility of common AHSS. The retained austenite of Q&P steels is rich in carbon and stable at room temperature. The heat treatment process implicates quenching the steel between the martensite-start (M_s) and martensite-finish (M_f) temperatures, followed by partitioning. Partitioning is an isothermal heat treatment that occurs above the M_s temperature. A diffusion process enriches the remaining austenite with carbon that migrates from martensite. The stability of retained austenite at room temperature improves the mechanical performance of steel, once it increases the material's toughness and elongation. The optimal control of microstructure originates the third generation of AHSS and enables to reduce of weight and improved mechanical response of automotive parts made of the TRIP and DP steels.
Keywords: Quenching and partitioning; AHSS; Retained austenite.

Resumo
Este manuscrito tem por objetivo apresentar uma visão geral do tratamento térmico de têmpera e partição (Q&P) geralmente aplicado aos aços de transformação induzida por plasticidade (TRIP) e aços duplex (DP). Os aços TRIP e DP são a primeira geração dos aços avançados de alta resistência (AHSS). Os aços AHSS apresentam uma microestrutura multifásica que garante uma combinação vantajosa de resistência e ductilidade. O processo de tratamento térmico de Q&P tem por objetivo obter uma microestrutura composta por martensita e austenita retida, de modo a melhorar a relação resistência/ductilidade do aço AHSS. A austenita retida dos aços Q&P é rica em carbono e estável e temperatura ambiente. O processo de tratamento térmico implica em temperar o aço entre a temperatura de início de transformação martensítica, M_s, e a temperatura final da transformação martensítica, M_f. Por um processo de difusão, o carbono da martensita migra para a austenita retida. A estabilidade da austenita retida em temperatura ambiente melhora o desempenho mecânico do aço, uma vez que há um aumento em sua tenacidade e alongamento. Este controle ótimo da microestrutura originou a terceira geração dos AHSS e permite a redução de peso e a melhora nas propriedades mecânicas de peças automotivas feitas em aços TRIP e DP.
Palavras-chave: Têmpera e partição; AHSS; Austenita retida.

Resumen
Este manuscrito tiene como objetivo presentar una descripción general del tratamiento térmico de temple y partición (Q&P) que generalmente se aplica a la plasticidad inducida por transformación (TRIP) y los aceros dúplex (DP). TRIP y DP son las primeras generaciones de aceros avanzados de alta resistencia (AHSS). Los AHSS presentan microestructuras multifásicas que aseguran una combinación ventajosa de resistencia y ductilidad. El proceso de tratamiento térmico Q&P tiene como objetivo obtener una microestructura mixta con martensita y austenita retenida y mejorar la relación resistencia/ductilidad del AHSS común. La austenita retenida de los aceros Q&P es rica en carbono y estable a temperatura ambiente. El proceso de tratamiento térmico implica el enfriamiento del acero entre las temperaturas de inicio de martensita (M_s) y de final de martensita (M_f), seguido de la partición. La partición es un

tratamiento térmico isotérmico que se produce por encima de la temperatura M_s. Un proceso de difusión enriquece la austenita restante con carbono que migra desde la martensita. La estabilidad de la austenita retenida a temperatura ambiente mejora el desempeño mecánico del acero, ya que aumenta la tenacidad y el alargamiento del material. El control óptimo de la microestructura da origen a la tercera generación de AHSS y permite reducir el peso y mejorar la respuesta mecánica de las piezas de automoción fabricadas con los aceros TRIP y DP.

**Palabras clave:** Temple y partición; AHSS; Austenita retenida.

1. Introduction

The main exigency of the automotive industry is always designing faster and safer cars, lowering carbon emissions (Yang *et al*., 2016). The design of new structural materials is the priority in this process. AHSS is a steel grade designed to meet this demand, as it exhibits a multiphase microstructure, resulting in an advantageous combination of strength and ductility. There are three generations of AHSS (Diego-Calderón *et al*., 2016). The first generation consists of ferrite-based steels and shows limited formability. Duplex (DP), transformation-induced plasticity (TRIP), complex phase (CP) and martensitic steels comprise this generation. The second generation comprises austenite-based steels, they are more formable, but much more expensive because of alloying elements costs and processing (Caballero *et al*., 2013). Austenitic stainless steels, twining induced plasticity (TWIP), and lighter weight steels with induced plasticity (LP-I®) are representatives of second grade. The third generation of HSLA embraces materials with intermediary properties between the first and second generations. The called third generation is formed by steels of the first generation when they are heat treated by the new process called Quenching and Partitioning (Q&P).

Speer *et al.* (2003) first described Q&P as novel heat treatment to produce steels containing mixtures of carbon-depleted martensite and carbon-enriched retained austenite. Stabilized retained austenite contributes positively to the properties of ferrous alloys, principally low alloy steels that can suffer from the deleterious effects of metastable austenite at room temperature (Edmonds *et al.,* 2006, Santofimia *et al*., 2008). The stability of retained austenite prevents its transformation with temperature or stress during service (Wu *et al.,* 2015). According to Yang *et al*. (2016), if a martensitic matrix presents more than a 5% volume fraction of retained austenite, it is already a noticeable improvement in material plasticity.

The Q&P process consists first in quenching the material at a temperature level between M_s and M_f temperatures (Bigg *et al*., 2013), to ensure some retained austenite content. Next, the part is heated up to a temperature slightly higher than M_s, when it suffers an isothermal heat treatment, the so-called partitioning (Wang *et al*. 2010). During partitioning, carbon migrates from supersaturated martensite to untransformed austenite (Santofimia *et al*., 2009). Finally, the steel is quenched to room temperature, resulting in a final microstructure with carbon-depleted martensite and carbon-enriched austenite. Figure 1 shows the Q&P process schematically.

Figure 1. Schematic of Q&P heat treatment.
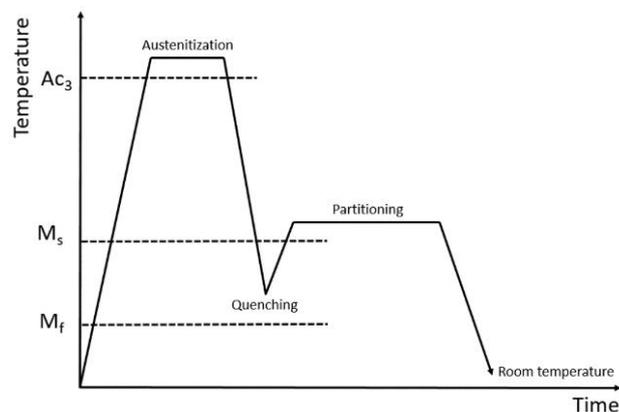
Source: Authors.

Three factors are fundamental to let retained austenite stable at room temperature: steel chemical composition, size and morphology of austenite, and surrounding phases (Kong *et al*., 2018, Podder *et al*., 2011).

Q&P has been attracting lots of attention in the last decade because it permits improving mechanical properties through an intelligent microstructure design. Second Forrest (2015) only in the USA, Q&P would save about 30 trillion Btu of energy by suppressing hot stamping manufacturing in the automotive industry. The transportation industry, in general, could reduce its fuel consumption, once Q&P steels present higher mechanical strength they can reduce the weight of parts made of steel (Diego-Calderón *et al*., 2016). Elongation presents an increase of up to 10% in Q&P steel.

Low alloy steel and Ni-Mn enriched TRIP steels are prone to let some portion of retained austenite and, literature has acclaimed the benefits of Q&P for these classes of steel. Q&P is also applicable for cast irons and martensitic stainless steels. (Nishikawa *et al*., 2016 and Tsuchiyama *et al*., 2012).

2. Methodology

This manuscript consists of a review work about quenching and partitioning heat treatment. The method is based on searching scientific papers in various indexing databases. The searching was done by the terms "quenching and partitioning", "mechanical properties of quenched and partitioned steels", and "constrained paraequilibrium condition". Google Scholar was the database used to do this work. It includes results of all the other databases, such as Scopus, Science Direct, and Web of Science, besides thesis and technical works. After analyzing the abstract section of the articles, the database was reduced to 42 papers. To enhance the discussion on topics about phase transformation other six classical references were added.

3. Temperature Selection

It is a concern that martensitic transformation occurs by a diffusionless process, didactically one can say that during quenching carbon does not have enough time to diffuse and form ferrite, so a diffusionless transformation occurs resulting in martensite. Nevertheless, it is common to reject the diffusion process that can occur near the M_s temperature. In this case, the diffusion process is commonly referred to form bainite; however, carbon can diffuse to austenite also, the so-called carbon partitioning process. Gouné *et al*. (2013) related that carbon partitioning from martensite into austenite is not a novelty, but Lu *et al*. (2013) explained that the mechanisms of carbon enrichment in retained austenite are not a concern. Matas and Hehemann (1960) reported evidence of these mechanisms. From the kinetic point of view, Gouné *et al*. (2013) demonstrated that partitioning is a diffusion-controlled process, that requires time in temperature. During Q&P the activation energy of carbon partitioning and austenite decomposition is 92 kJ/mol and 172 kJ/mol respectively (De Moor *et al*., 2010). The desire is to control the process of carbon partitioning to get the best mechanical properties. Assuming that partitioning is a diffusion process, a range of temperatures is necessary to eliminate the supersaturation of carbon in martensite, but it can permit epsilon carbide precipitation or bainite formation. An ideal process should suppress bainite and carbide precipitation.

Design of the Q&P process starts with M_s temperature determination by experimental tests or by an empirical equation based on chemical composition such as:

$$M_s = 539 - 423C - 30,4Mn - 7,5Si - 7,5Mo + 30Al \tag{1}$$

Quenchant temperature should be a value below M_s and must be selected to produce a determined fraction of martensite and the maximum amount of retained austenite (Seo *et al*., 2016, Edmonds *et al*., 2006). Andrews (1965) proposed Eq. (1). For

ideal processes, *i.e.*, only martensite and austenite result from the quenching process, the Koinstinen-Marburger relationship predicts the fraction of martensite (Clarke *et al.*, 2008):

$$f_M^{QT} = 1 - e^{-1,1 \times 10^{-2}(M_s - QT)}$$ (2)

where f_M^{QT} is the fraction of transformed martensite from austenite, QT is the quenchant temperature, and M_s is the temperature when martensite starts the transformation. The temperature unit is Kelvin.

The empirical approximation of retained austenite fraction at room temperature for Q&T steels is different from experimental measurements, Lu *et al.* (2013) emphasize that we do not have a satisfactory model for carbon partitioning kinetics. The high velocity that the partitioning process takes place is the major complication in characterizing it, in a few minutes it is complete (Lu *et al.*, 2013). The lack of an efficient experimental method to capture the carbon-partitioning process explains the interest in determining empirical equations to determine the heat treatment temperature. The fraction of retained austenite, f_γ^{QT}, could be determined by:

$$f_\gamma^{QT} = 1 - f_M^{QT}$$ (3)

Avoiding bainite transformation during isothermal heat treatment is also necessary. Equation (4) predicts bainite start (B_s) temperature transformation as a function of chemical composition (Lee, 2002). Partitioning temperature should be in a range between M_s and B_s.

$$B_S = 830 - 270C - 90Mn - 70Cr - 37Ni - 83Mo$$ (3)

In theory, these relations would be valid if only martensite and austenite are present on the as-quenched microstructure. In most cases, corrections assume the presence of intercritical ferrite. Fractions of ferrite and bainitic ferrite can be estimated from experimental data of ferrite carbon concentration and initial and final austenite carbon concentration using the cantilever rule (Clarke *et al.* 2008). Carbon partitioning also occurs from bainitic ferrite to austenite (Bhadeshia, 2001). Equations (5) and (6) are mass balance expressions that estimate the volume fractions of bainitic ferrite (f_α^b) and austenite (f_γ^b) (Santofimia *et al.*, 2009):

$$f_\alpha^b = \left(\frac{C_\gamma - C_\gamma^{IC}}{C_\gamma - C_\alpha} \right) f_\gamma^{QT}$$ (5)

$$f_\gamma^b = \left(\frac{C_\gamma^{IC} - C_\alpha}{C_\gamma - C_\alpha} \right) f_\gamma^{QT}$$ (6)

where the carbon content in retained austenite, initial austenite (before quenching), and bainitic ferrite are C_γ, C_γ^{IC}, and C_α respectively.

Clarke *et al.* (2009) punctuate that the challenge is to find the optimum quench temperature. Less martensite remains after quenching because above the ideal temperature considerable austenite volume fractions form. As consequence, the carbon available is not enough to stabilize the austenite at room temperature. They also reported that quenching below the optimum temperature deteriorates the ductility of the material, once martensitic transformation consumes almost all austenite.

Furthermore, the Koinstinen-Marburger relationship is useful in predicting some process variables; it does not describe partitioning kinetic. Lee and Van Tyne (2012) proposed some modifications to the Koinstinen-Marburger equation, by adding K_{LV} and n_{LV} parameters, which are a function of chemical composition. Parameter n_{LV} is dimensionless and the unit of K_{LV} is K^{-1}.

$$f_\alpha^b = 1 - e^{-K_{LV}(M_S - QT)^{n_{LV}}} \tag{7}$$

$$K_{LV} = 0{,}0231 - 0{,}0105C - 0{,}0017Ni + 0{,}0074Cr - 0{,}0193Mo \tag{8}$$

$$n_{LV} = 1{,}4304 - 1{,}1836C + 0{,}7527C^2 - 0{,}0258Ni - 0{,}0739Cr + 0{,}3108Mo \tag{9}$$

Table 1 shows the range of chemical compositions that can be successful using the Lee-Van Tyne (LV) equation. According to Seo *et al*. (2016), this model is more accurate to describe the athermal martensite transformation. The amounts of Mn and Si are average values of plain carbon and low alloyed steels chemical compositions.

Table 1. Chemical composition range for LV model

C	Ni	Cr	Mo	Mn	Si
0,2 – 1,2	0,0 – 2,1	0,0 – 1,2	0,0 – 0,3	0,75	0,25

Source: Lee and Van Tyne, 2012.

Unfortunately, the models presented above deal only with ideal processes. Although they can provide a good approximation, it is important to admit the possibility of the occurrence of carbide precipitation (Toji *et al*., 2015).

4. Thermodynamics of Partitioning Process

Any quenched steel presents a metastable microstructure, and another heat treatment process is necessary to stabilize the microstructural system. Traditionally, the steel heat treatment sequence is quenching followed by tempering. During tempering martensite loses carbon and some carbides precipitate. Partitioning also intends to let a stabilized microstructure. It differs from tempering because it avoids carbide precipitation, and the expected microstructure is martensite and carbon enriched retained austenite. Carbide precipitation should reduce the amount of carbon obtainable for partition.

Austenite's morphology determines the mechanism of carbon enrichment. Film-like retained austenite usually is located between martensite laths, and carbon migrates from martensite to austenite during isothermal holding. Film austenite is richer in carbon (Podder *et al*., 2011). The carbon partitioning process of block retained austenite comprises two steps: first during partial austenitization, and later the stabilization occurs during the isothermal process. Block retained austenite remains in the ferrite grain boundaries (Kong *et al*., 2018). Because of the TRIP effect, block retained austenite transforms into martensite (Zinsaz-Borujerdi *et al*., 2018). Q&P steels exhibit both morphologies types.

Speer *et al*. (2003) described the thermodynamics of carbon partition using the constrained paraequilibrium condition (CPE). If the system were under a thermal equilibrium condition, ferrite and carbide should be the resulting microstructure from martensite and retained austenite. Iron and substitutional atoms never diffuse during partitioning because, due to their size, the energy is not enough. Because of this carbide precipitation never occurs. When it occurs, the interface martensite/austenite has a fixed position. Gibbs's free energy is minimal during carbon partitioning, and the chemical potential of carbon is identical between both phases (Tsuchiyama *et al*., 2012). Hillert and Ågren (2004) suggested calling CPE of constrained carbon

equilibrium (CCE), once paraequilibrium means constrained. Toji *et al*. (2015) summarized three conditions as the base of this criterion (CCE). The first condition consists in neglecting that any competing reaction happens during carbon partitioning. The second one is to assume that carbon from martensite and austenite have the same chemical potential. A third condition consists in assuming that carbon does not migrate between austenite/ferrite interfaces. CCE theory predicts the final austenite carbon concentration, at the end of the process (Toji *et al*., 2015). This theory may be applied to steel when carbide formation is suppressed (Speer *et al*., 2003).

Toji *et al*. (2015) modified the CCE model by considering the occurrence of carbide precipitation. This model was named CCEθ, where θ is related to carbide precipitation. They considered that cementite precipitates inside martensite, in this way, ferrite and cementite have the same carbon potential. To maintain the equilibrium carbon potential in austenite should be the same in ferrite. CCEθ also considers that the interface between ferrite and austenite remains the same and the thermodynamic conditions determine carbon content in austenite.

If non-stable retained austenite remains after processing, it can transform into martensite (Kähkönen, 2016). The Gibbs free energy is a function of the temperature diagram for this transformation. Transformation occurs spontaneously below M_s temperature and at T1 transformation requires a mechanical driving force (Kähkönen, 2016).

5. Process Variables

5.1 Chemical composition

De Knijf *et al*. (2015) describe that chemical composition design for Q&P steels should attend to three basic rules: (i) alloying elements should avoid ferrite, perlite, or bainite during quenching and bainite during partitioning; (ii) suppress carbide precipitation; and (iii) stabilize the austenite during final quenching. In practice, carbide precipitation can happen during the partition process (Bhadeshia and Edmonds, 1979; Toji *et al*., 2015). The main reason why it is necessary to add some chemical elements to steel is to avoid carbide precipitation.

Speer *et al*. 2003 related that carbon diffusion from martensite to austenite happens to thin interlath films during cooling or by isothermal holding in Si-containing steel after transformation.

Silicon has a decisive role in austenite stabilization at room temperature. Al and Si suppress carbide formation during partitioning (Santofimia *et al*., 2009). However, De Moor *et al*. (2006) reported that aluminum could reduce the stability of retained austenite at long partitioning times. Santofimia *et al*. (2008) highlighted that Al is efficient in avoiding cementite precipitation, but its effects on transition carbides are unknown. Gaudez *et al*. (2018) related that aluminum increases partitioning kinetics because it increases the carbon content at the interface. Kähkönen (2016) stated that aluminum increases stacking fault energies which inhibit strain-induced α'-martensite nucleation. Si also increases ferrite tensile strength.

Manganese inhibits ferrite transformation from austenite at high temperatures (Gao *et al*., 2016, Masek *et al*., 2010). This element also increases the steel hardenability, acts as a mild carbide-forming element, and diminishes bainite growth kinetics (Kähkönen, 2016). These characteristics make Mn an alloying element very used in Q&P steels. Although Mn improves yield strength, elongation levels are lower than expected for quenched and tempered steels (De Moor *et al*., 2011). Ideal Mn content should range between 0.6 to 1.2 wt% for avoiding elongation loss, but high Mn concentrations can lead to segregation banding (De Knijf *et al*., 2015).

Nickel diminishes Ms transformation temperature and propitiates an increase in the amount of retained austenite (Lu *et al*. 2013). Rizzo *et al*. (2007) reported that high nickel alloys present low ductility.

Molybdenum improves hardenability (De Moor *et al*., 2009). Retained austenite, in these cases, will present a lower concentration of carbon, but it is stable because of thin lath martensite (Kobayashi *et al*., 2012).

Possibly, phosphorus and cobalt do not affect CPE conditions (Gaudez *et al*., 2018).

Carbon is the most important chemical element that stabilizes austenite in low alloy steels (Wu *et al*., 2015, De Moor *et al*., 2011). It is necessary to facilitate the partition process and to improve the hardenability. Carbon content also changes the M_s temperature (Eq. 1) and consequently the volume fraction of retained austenite. In this way, steels with high carbon content tend to suffer martensitic transformation at lower temperatures. Carbon content determines martensite morphology. Lath and plate types are found in low and high carbon steels respectively. Carbon and nitrogen increase ferrite yield strength while chromium has a deleterious effect on this property. Chromium also diminishes carbon partitioning kinetics (Gaudez *et al*., 2018). The interstitial atoms (C and Ni) has more effect than the substitutional ones (Si, Cu, and Mo) (Kähkönen, 2016).

5.2 Cooling rate

Santofimia *et al*. (2009) reported that the cooling rate after quenching influences the volume fraction of the austenite available for partitioning, as the formation of epitaxial ferrite. Epitaxial ferrite forms at lower cooling rates and its presence result in a reduction of austenite fraction available for the partitioning process, although it can lead to additional carbon enrichment of austenite. The cooling rate should be high enough to avoid ferrite and perlite transformation. High thermal gradients can introduce residual stress in the quenched part because this cooling rate must be carefully selected to result in better microstructure and mechanical properties design. Reducing internal stresses of first quenching, they do not affect martensite transformation after partitioning (Santofimia *et al*., 2008).

5.3 Time and temperature

Quenching temperature is a critical parameter because it determines the amount of carbon available for partitioning based on the volume fraction of retained austenite and martensite (Clake *et al*., 2009). Generally, the heat treatment process is designed to produce 50% of martensite and austenite. For Gerdemann, 2004, for each carbon content, there is an optimum quench temperature that results in a higher fraction of retained austenite. For example, for steels with 0.2 wt pct of carbon, the ideal temperature should be 250°C to get 0.2 of austenite. Koopmans, 2015, found that austenite lattice increases for lower quenching temperatures.

Austenitizing temperature influences the M_s temperature and prior grain size. Low austenitizing temperature produces fine prior austenite grain, tends to produce a larger volume fraction of retained austenite, and ensures a microstructure more uniform (Zhao *et al*., 2017). The larger prior austenite grain increases the M_s temperature. The probability of carbon and alloy elements going into a solid solution is greater when the austenitizing temperature is higher. In this case, the carbon content in austenite increases, and the M_s temperature decreases.

Partitioning temperature is between the temperatures M_s and B_f. Selecting this range of temperature is a common practice, especially when it is necessary to avoid bainite transformation, although higher temperatures facilitate the diffusion process.

The time necessary to decarburize martensite depends on partitioning temperature. Higher isothermal temperature demands less time to complete the process. Heat treaters should select the time process carefully because the carbon content of retained austenite reduces as partitioning time grows (Santofimia *et al*., 2009). It indicates a probability of carbide precipitation for a long time of isothermal treatment.

6. Mechanical Properties

The maximum volume fraction of retained austenite does not propitiate optimum mechanical properties (Liu *et al*. 2018). Ideal microstructure comprises fine martensite laths and thin austenite films. Lath martensite anchors dislocations and the corresponding yield strength increases (Zinsaz-Borujerdi *et al*., 2018).

Elongation is the mechanical property most benefited by the Q&P process. Quenched and partitioned steels exhibit an increase of 10% in elongation. The hot working of Q&T steels varies significantly with temperature, and it is associated with retained austenite stability (Luo *et al*., 2017). Koopmans (2015) related that film-like retained austenite is more stable under stress than larger retained austenite. The ductility improves because of this. Olson-Cohen model describes the mechanical stability of retained austenite (Liu *et al*., 2018; Oslon and Cohen, 1975).

$$f_{\alpha\prime} = 1 - e^{\left\{-\beta(1-e^{-\alpha\varepsilon})^2\right\}}$$ (10)

Where $f_{\alpha\prime}$ is the volume fraction of martensite transformed by plastic deformation, α, β and ε are constants depending on the tensile test temperature.

Partitioning also relaxes internal stresses due to martensite transformation during the first quenching (Santofimia *et al*., 2009). Allain *et al*., 2018, showed that retained austenite presents a compressive stress state at the end of the Q&P process. They also noticed that internal compressive stresses inhibit martensite strain-induced transformation.

Studies performed in very high cycle fatigue indicate that quenched and partitioned steels rarely break before 10^9 cycles (Gao *et al*., 2016). It is possible because stabilized austenite does not undergo to martensite due plastic deformation.

Diego-Calderón *et al*. (2016) reported that any factor that determines retained austenite stabilization controls the fracture behavior. They enumerated the following factors: carbon concentration, grain size, the constraining effect of the surrounding phases, and its morphology. Q&P steels exhibit a better fracture resistance, and it slightly increases for samples with a higher volume fraction of retained austenite. Toughness presents the same tendency.

Yang *et al*. (2016) reported that hydrogen embrittlement resistance improves for Q&P steels. They explain that the high stability of retained austenite retards hydrogen diffusivity and the increasing area of interfacial boundaries, slightly impairs hydrogen diffusivity and solubility in martensite. However, Lovicu *et al*. (2013) showed that Q&P medium carbon samples presented higher hydrogen embrittlement.

7. Conclusion

The Q&P heat treatment process is the best and unique way to improve the mechanical properties of low alloy steels. This process is the only way to increase the elongation of low alloy steel by about 10%, with some gain in strength. Any improvement in elongation means that the material gets more formable at room temperature. If it occurs, hot stamping becomes unnecessary, and therefore, the costs would reduce.

Selecting the appropriate manufacturing parameters is crucial to achieving the desired mechanical properties from the Q&P process. The Q&P critical parameters are temperature and holding time at temperature. Much more research is needed to formulate physical models and better optimize the manufacturing process for each steel chemical composition.

The industrial adoption of the Q&P process is very restricted, despite its feasibility. It happens because the process is relatively new, heat treaters do not know all the possibilities of the Q&P process, and the other one is the absence of a physical model to aid the design of manufacturing planning and control.

Future research must focus on getting a physical model to describe the Q&P process, further study in welding, and the mechanical properties of Q&P steel.

References

Allain, S. Y. P., Gaudez, S., Geandier, G., Hell, J. C., Gouné, M., Danoix, F., & Poulon-Quintin, A. (2018). Internal stresses and carbon enrichment in austenite of Quenching and Partitioning steels from high energy X-ray diffraction experiments. *Materials Science and Engineering: A*, 710, 245-250.

Andrews, K. W. (1965). Empirical formulae for the calculation of some transformation temperatures. *J. Iron Steel Inst.*, 721-727.

Bhadeshia, H. K. D. H. (2001). Bainite in steels (2a ed.), *The Institute of Materials, London.*

Bhadeshia, H., & Edmonds, D. (1979). The bainite transformation in a silicon steel. *Metallurgical Transactions A*, 10, 895–907.

Bigg, T., Edmonds, D., & Eardley, E. (2013). Real-time structural analysis of quenching and partitioning (Q&P) in an experimental martensitic steel. *Journal of Alloys and Compounds*, 557S, S695-S698.

Caballlero, F., Allain, S., Cornide, J., Puerta -Velasquez, J., Garcia-Mateo, C., & Miller, M. (2013). *Mater. Des.*, 49, 667-680.

Clarke, A., Miller, M., & Hackenberg, R. (2008). Carbon partitioning to austenite from martensite or bainite during the quench and partition (Q&P) process: A critical assessment. *Acta Materialia*, 56, 16-22.

Clarke, A., Speer, J., Matlock, D., Rizzo, F., Edmonds, D., & Santofimia, M. (2009). Influence of carbon partitioning kinetics on final austenite fraction during quenching and partitioning. *Scripta Materialia*, 61, 149-152.

De Knijf, D., DaSilva, E., Föjer, C., & Petrov, R. (2015). Study of heat treatment parameters and kinetics of quenching and partitioning cycles. *Materials Science and Technology*, 31, 817-828.

De Moor, E., Föjer, C., Penning, J., Clarke, A., & Speer, J. (2010). Calorimetric study of carbon partitioning from martensite into austenite. *Physical Review B*. 82, 1-5.

De Moor, E., Lacroix, S., Samek, L., Penning, J., & Speer, J. (2006). Dilatometric Study of the Quench and Partitioning Process. *The 3rd International Conference on Advanced Structural Steels*. Gyeongju, Korea, august.

De Moor, E., Speer, J., Föjer, C., & Penning, J. (2009). Effect of Si, Al, Mo alloying on tensile properties obtaned by quenching and partitioning. *Proceedings of Materials Science and Technology*, 1554-1563.

De Moor, E., Speer, J., Matlock, D., Kwank, J., & Lee, S. (2011). Effect of carbon and manganese on the quenching and partitioning response of CMnSi steels. *ISII International*, 51, 137-144.

Diego-Calderón, I., Sabirov, I., Molina-Aldagueria, J., Föjer, C., & Thiessen, R. (2016). Microstructural design in quenched and partitioned (Q&P) steels to improve their fracture. *Materials Science & Engineering A*, 657, 136-146.

Edmonds, D., He, K., Rizzo, F., De Cooman, B., Matlock, D., & Speer, J. (2006). Quenching and partitioning of maternsite - a novel heat treatment. *Materials Science and Engineering A*, 438-440, 25-34.

Forrest, D. (2015). *Quenching and partitioning process development to replace hot stamping of high- strength automotive steel.* Factsheet: U.S. Department of Energy.

Gao, G., Zhang, B., Cheng, C., Zhao, P., Zhang, H., & Bai, B. (2016). Very high cicle fatigue behaviors of bainite/martensite multiphase steel treated by quenching-partitioning-tempering process. *International Journal of Fatigue*, 92, 203-210.

Gaudez, S., Teixeira, J., Allain, S. Y., Geandier, G., Gouné, M., Soler, M., & Danoix, F. (2018). Numerical Investigations of the Effects of Substitutional Elements on the Interface Conditions During Partitioning in Quenching and Partitioning Steels. *Metallurgical and Materials Transactions A*, 1-5.

Gerdemann, F. (2004). Microstructure and Hardness of 9260 Steel Heat-Treated by the Quenching and Partitioning Process. "Diploma Thesis", 2004, "Aachen University of Technology (RWTH) Germany.

Gouné, M., Danoix, F., Allain, S., & Bouaziz, O. (2013). Unambiguous carbon partiting from matensite to austenite in Fe-C-Ni alloys during quenching and partitioning. *Scripta Materialia*, 68, 1004-1007.

Hillert, M., & Ågren, J. (2004). On the definitions of paraequilibrium and orthoequilibrium. *Scripta Materialia*, *50*(5), 697-699.

Kähkönen, J. (2016). Quenching and partitioning response of carbon-manganese-silicon sheet steels containing nickel, molybdenum, aluminum and copper additions. Dissertation. Colorado School of Mines.

Kobayashi, J., Ina, D., Yoshikawa, N., & Sigimoto, K. (2012). Effects of the Addition of Cr, Mo and Ni on the Microstructure and Retained Austenite Characteristics of 0.2% C–Si–Mn–Nb Ultrahigh-strength TRIP-aided Bainitic Ferrite Steels. *ISIJ International*, 52, 1894-1901.

Kong, H., Chao, Q., Cai, M. H., Pavlina, E. J., Rolfe, B., Hodgson, P. D., & Beladi, H. (2018). Microstructure Evolution and Mechanical Behavior of a CMnSiAl TRIP Steel Subjected to Partial Austenitization Along with Quenching and Partitioning Treatment. *Metallurgical and Materials Transactions A*, 49(5), 1509-1519.

Koopmans, T. (2015). Thermal stability of retained austenite in Quenching and Partitioning steels. Master, 77p.: Faculty of Mechanical, Maritime and Materials Engineering / Delft University of Technology.

Lee, S., & Van Tyne, C. (2012). A kinetics model for martensite transformation in plain carbon and low-alloyed steels. *Metallurgical and Materials Transactions A*, 42, 442-427.

Liu, L., He, B. B., Cheng, G. J., Yen, H. W., & Huang, M. X. (2018). Optimum properties of quenching and partitioning steels achieved by balancing fraction and stability of retained austenite. *Scripta Materialia*, 150, 1-6.

Lee, Y. K. (2002). Empirical formula of isothermal bainite start temperature of steels. *Journal of Materials Science Letters*, 21(16), 1253-1255.

Lovicu, G., Bagliani, E., DeSanctis, M., Dimatteo, A., Ishak, R., & Valentini, R. (2013). Hydrogen embrittlement of a medium carbon Q&P steel. *La Metallugia Italiana*, 6, 3-10.

Lu, X., Liu, H., & Jin, X. (de 2013). Preliminary study on kinetics of cabon partitioning in high Ni Q&P steel. *Journal of Alloys and Compounds*, 577S, S72-S75.

Luo, L., Li, W., Gong, Y., Wang, L., & Jin, X. (2017). Tensile behavior and deformation mechanism of quenching and partitioning treated steels at different deforming temperature. *Journal of Iron and Steel Research, International*, 24, 104-1108.

Masek, B., Jirková, H., Hauserova, D., Kucerova, L., & Klauberiva, D. (2010). The effect of Mn and Si on properties of advanced high strength steels processed by quenching and partitioning. *Materials Science Forum*, 654-656, 94-97.

Matas, S., & Hehemann, R. F. (1960). Retained austenite and the tempering of martensite. *Nature*, 187, 685–686.

Nishikawa, L., Melado, A.C., Goldenstein, H., Bauri, L.F., dos Santos Filho, D. & Nunes, E. (2016). Enhancing mechanical properties of ductile cast iron conrods through different heat treatments. (No. 2016-36-0360). *SAE Technical Papers*. SAE International.

Olson, G. B., & Cohen, M. (1975). Kinetics of strain-induced martensitic nucleation. *Metallurgical transactions A*, 6(4), 791.

Podder, A. S., Lonardelli, I., Molinari, A., & Bhadeshia, H. K. D. H. (2011). Thermal stability of retained austenite in bainitic steel: an in situ study. *Proc. R. Soc. A*, 467(2135), 3141-3156.

Rizzo, F., Martins, R., Speer, J., Matlock, D., Clarke, A., and DeCooman, B. (2007). Quenching and partitioning of Ni added high strength steels. *Materials Science Forum. Trans Tech Publications*, 539, 4476-4481.

Santofimia, M., Zhao, L., & Sietsma, J. (2009). Microstructural evolution of a low-carbon steel during application of quenching and parttioning heat treatments after partial austenitization. *Metallurgical and Materials Transactions A*, 40, 46-56.

Santofimia, M., Zhao, L., Petrov, R., & Sietsma, J. (2008). Characterization of the microstructure obtaned by the quenching and partitioning process in a low-carbon steel. *Materials Characterization*, 59, 1758-1764.

Seo, E., Cho, L., & Decooman, B. (2016). Modified metodology for quench temperature selection in quenching and partitioning (Q&P) processing of steels. *Metallurgical and Materials Transactions A*, 47A, 3797-3802.

Speer, J., Matlock, D., De Cooman, B., & Schroth, J. C. (2003). Carbon partitioning into austenite after martensite transformation. *Acta Materialia*, 51, 2611-2622.

Toji, Y., Miyamoto, G., & Raabe, D. (2015). Carbon partitioning during quenching and partitioning heat treatment accompanied by carbide precipitation. *Acta Materialia*, 86, 137-147.

Tsuchiyama, T., Tobata, J., Tao, T., Nakada, N., & Takaki, S. (2012, 532). Quenching and partitioning treatment of a low-crbon martensitic stainless steel. *Materials Science and Engineering A*, 532, 585-592

Wang, C., Shi, J., Cao, W., & Dong, H. (2010). Characterization of microstruture obtained by quenching and partitioning process in low alloy martensitic steel. *Materials Science and Engineering A*, 527, 3442-3449.

Wu, R., Li, W., Wang, C., Xiao, Y., Wang, L., & Jin, X. (2015). Stability of retained austenite through a combined intercritical anneling and quenching and partitioning (IAQP) treatment. *Acta Metall. Sin. (Engl. Lett.)*, 28, 286-393.

Yang, Y., Huang, F., Guo, Z., Rong, Y., & Chen, N. (2016). Effect of retained austenite on the hydrogen embrittlement of a medium carbon quenching and partitioning steel with refined microstructure. *Materials Science and Engineering A*, 665, 76-85.

Zhao, Z. Z., Liang, J. H., Zhao, A. M., Liang, J. T., Tang, D., & Gao, Y. P. (2017). Effects of the austenitizing temperature on the mechanical properties of cold-rolled medium-Mn steel system. *Journal of Alloys and Compounds*, 691, 51-59.

Zinsaz-Borujerdi, A., Zarei-Hanzaki, A., Abedi, H. R., Karam-Abian, M., Ding, H., Han, D., & Kheradmand, N. (2018). Room temperature mechanical properties and microstructure of a low alloyed TRIP-assisted steel subjected to one-step and two-step quenching and partitioning process. *Materials Science and Engineering: A*, 725, 341-349.