

Process Design for Quenching and Partitioning of Plate Steels

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INTRODUCTION

The “quenching and partitioning” (or Q&P) process has been developed to produce high strength steel microstructures with substantial quantities of retained austenite. Q&P is being applied industrially as one way to produce third generation advanced high strength steels (AHSS), a class of sheet steels^[1] with excellent combinations of strength and formability^[2]. Microstructures containing retained austenite are also of interest in wear applications,^[3, 4] and so are relevant to plate steel production for construction machinery, agricultural and other earth engaging applications. The enhancement of ductility, toughness or wear resistance is intended to derive from transformation of the retained austenite to hard martensite during deformation that occurs during manufacturing or service, *i.e.* the TRIP (TRansformation Induced Plasticity) effect.

A schematic of the Q&P process applicable to sheet steel annealing is given in Figure 1. The process involves austenitizing and then quenching to a carefully controlled “quench temperature” (QT) between the martensite start and martensite finish (M_s and M_f) temperatures, to generate a desired mixture of martensite and untransformed austenite, followed by “partitioning” for a given time (Pt) at temperature (PT) to transport a substantial portion of the carbon from the martensite into the austenite, where it is more soluble. The increased carbon concentration stabilizes austenite, thus increasing the fraction of austenite retained upon final cooling to room temperature^[5, 6].

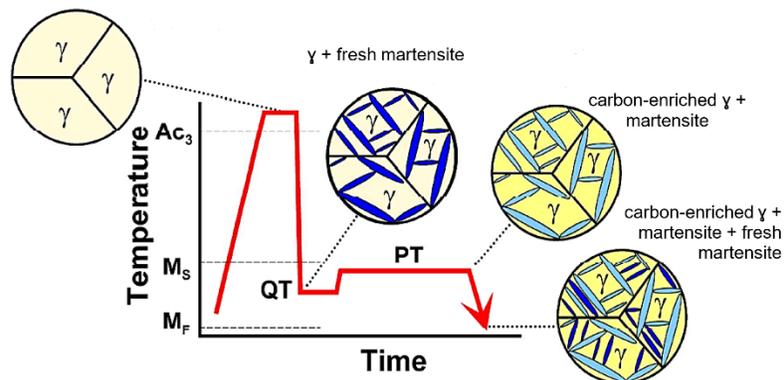


Figure 1. Schematic of Q&P sheet processing, with full austenitization, showing expected microstructures at each step. QT and PT are quenching and partitioning temperatures, respectively. M_s and M_f are martensite start and finish temperatures, respectively^[7].

A method has been developed to predict final Q&P microstructures for idealized conditions where mechanisms competing with carbon partitioning (such as carbide precipitation during tempering) are completely suppressed. The method is described elsewhere, and predicts the fraction and carbon content of the retained austenite, as well as the fraction of “partitioned” martensite and the fraction of “fresh” carbon enriched martensite expected to form during final cooling^[8]. Figure 2 shows example results for a hypothetical steel containing 0.2 wt. pct. carbon with an M_s temperature of 400°C. The predicted fraction of retained austenite (γ_{final}) is shown with the bold curve, where the peak at about 250°C is often referred to as the “optimum” QT, which corresponds to a maximum retained austenite content of about 19 vol. pct in this case.

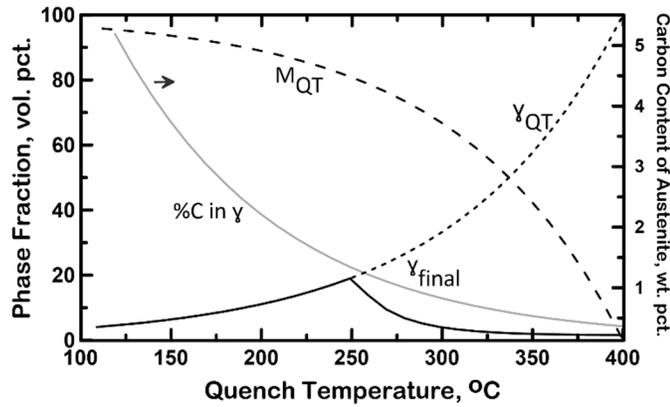


Figure 2. Calculated phase fractions as a function of initial quench temperature in a hypothetical Q&P process with idealized full partitioning. Phase fractions are calculated for a 0.2 wt. pct. C steel with $M_s = 400$ °C. M_{QT} and γ_{QT} correspond to the amount of martensite and austenite present after quenching to QT. γ_{final} predicts the final austenite phase amount after final cooling to room temperature. The carbon content in the initial and retained γ after idealized partitioning is indicated on the second y axis.

The Q&P process concept was later extended to hot-rolled sheet processing, where the thermal history is different than the schematic shown in Figure 1. Thomas and co-workers^[9] developed the concept for Q&P hot-rolled sheet production, using coil cooling to control both the quenching and partitioning steps. Thomas *et al.* noted the challenge in controlling the variability of microstructure and properties across the width and length of steel sheets that arise during coil cooling^[9], due to cooling rate variations. Work in hot-rolled sheet Q&P has been extended more recently, and applied industrially for cement mixer trucks, where material loss due to wear was minimal^[10].

A small number of studies have considered the possibility of applying Q&P in steel plate^[11–13]. Hong *et al.* obtained Q&P microstructures with attractive properties in laboratory heat treated plate, suggesting the opportunity for thick plate Q&P^[11]. Zhou *et al.* examined temperature and microstructural gradients in hot rolled plate through thermal modeling and experimental validation^[12]. The simulated thermal profiles predicted an inhomogeneous microstructure through a 20 mm thick steel sample after a quench-partition-temper (Q-P-T) process (austenitizing for 3600 s, quenching for 15 s then tempering by air cooling for 1800 s). Experimental results confirmed this prediction: a “sandwich” microstructure was reported with lath martensite at the plate surfaces/subsurface and a mixture of lath martensite and bainite in the center where the steel cooled more slowly. This inhomogeneity in microstructure in the 20 mm thick sample was neither predicted nor experimentally observed in a 12 mm thick sample, which showed similar microstructures (martensite laths) throughout the cross section.

The above studies suggest that microstructural variations may arise through the thickness in Q&P processing of thicker plates, due to variation in cooling rates and resulting thermal gradients. While the quench temperature (QT), partitioning temperature (PT) and partitioning time (Pt) can be controlled in modern sheet annealing processes, in plate Q&P these parameters are less defined; a range of QT-PT-Pts and therefore a range of microstructures is expected to arise through the thickness. Control of microstructure and properties in Q&P plate therefore requires a deep understanding of the evolving thermal gradients. This situation presents an important opportunity for a thermal model to be developed and applied as a tool to explore the effects of plate thickness, quench rates and reheat on the thermal history and resulting microstructure development.

This work focuses on the development and application of such a thermal model to investigate thermal gradients induced during plate Q&P processing. Cooling profiles produced under various thickness and process conditions are simulated and the effects of thermal gradients on final microstructures (assuming idealized partitioning) are investigated. The model is extended here to incorporate a furnace reheating step that might be envisioned to provide a viable partitioning process step.

While thin sheet can be heated and cooled rapidly and held under nearly isothermal processing conditions, industrial plate cooling is inherently non-isothermal with thermal gradients persisting until the plate temperature eventually equilibrates at room temperature. Room temperature is generally not a suitable Q&P quench temperature, so variations in quench temperature through the cross-section are expected to be “normal” for thick plates, as demonstrated below. There is no “partitioning” step built into industrial plate production facilities, and the most common plate reheating step is associated with tempering of martensite after quenching to room temperature. Furnace reheating over tens of minutes is much longer than the partitioning treatments associated with industrial sheet processing. Isothermal partitioning is not likely to be possible for furnace heating, so a non-isothermal partitioning model is needed to design a plate Q&P process.

NON-ISOTHERMAL PLATE PARTITIONING

Non-isothermal partitioning was first considered by Thomas *et al.* [9]. The thermal history of the coiling step was converted into an “equivalent” isothermal time-temperature history, using the Holloman-Jaffe tempering parameter (TP), which is a well-known and commonly-employed means of representing tempering time-temperature equivalence. Equation 1 describes the empirically developed Hollomon-Jaffe tempering parameter (TP) for non-isothermal tempering conditions, where TP_o is the tempering parameter at the beginning of a time step, T is temperature in Kelvin, t is time in hours and c is a carbon dependent constant, selected as 19.0 for the present study [14].

$$TP = T \left(\log \Delta t \times 10^c + 10^{TP_o/T} \right) \quad (1)$$

The tempering parameter expression in Equation 1 can be integrated along any thermal path considered to represent a partitioning step, to define the TP value for that partitioning process. This TP value can be compared with TP values from isothermal (time at temperature) heat treatments that are known from literature or by experiment to provide a suitable partitioning response. This methodology was used to predict TP values for furnace partitioning that may apply to industrial heating conditions.

THERMAL MODELING PROCEDURE

A simple one-dimensional finite-difference model was developed to simulate temperature evolution during the cooling of a flat steel plate [15]. For a typical flat plate, where the thickness is small compared to plate length and width, the steepest temperature gradients are expected to develop through the thickness.

Transient heat conduction through a solid flat plate is described by Fourier’s transient-conduction equation. The solution to this partial differential equation provides the variation of temperature with both time and position in the plate needed to predict the microstructure. In the absence of internal heat generation, and assuming constant thermal properties, the 1-D Fourier’s equation is:

$$\frac{dT}{dt} = \alpha \frac{d^2T}{dx^2} \quad (2)$$

where T is temperature, t is time, x is the plate thickness, and α is thermal diffusivity, defined as:

$$\alpha = \frac{k}{\rho C_p} \quad (3)$$

where k is conductivity, ρ is density and C_p is specific heat.

The imposed boundary conditions for the cooling of the plate were forced convection with convection coefficient, h , at the top and bottom plate surfaces. The finite-difference model solution to Equation 1 was evaluated numerically by discretizing the domain into ~50 cells and performing an energy balance on each cell, as reported earlier [15]. Expressions for temperature were obtained for each cell through the plate thickness (established based on a mesh size study). A transformed version of the heat transfer equations was coded in MATLAB and solved using the built-in MATLAB ordinary differential solver (ODE45). This numerical model was verified against an analytical solution, and matched within 0.001 pct. maximum error. Physical constants selected for the “severe” water quenching model are summarized in Table I.

More recently, the numerical model was extended to simulate temperature evolution during a furnace partitioning step following the initial plate cooling step. A second component was added to the boundary condition at the plate surfaces to include radiation gained from the furnace interior, according to Stefan-Boltzmann’s relation:

$$q = h(T_\infty - T_{surf}) + \varepsilon \sigma (T_\infty^4 - T_{surf}^4) \quad (4)$$

where q is the rate of energy transferred to the plate surface, (W/m^2), ε is emissivity, h is the average convection coefficient, σ is the Stefan- Boltzman constant, T_∞ is ambient temperature, T_{surf} is the current plate surface temperature [16]. Typical convection coefficients of 10 W/m^2K and 40 W/m^2K [17] were selected to represent air cooling during a brief holding step before furnace entry and furnace reheating, respectively. A constant emissivity of 0.8 was applied during furnace reheating [16, 18]. In

the extended model, a built-in MATLAB ordinary differential solver (ODE23s) for stiff equations was used to obtain temperature profiles. The thermal signature during reheating/partitioning could thus be estimated based on the furnace temperature and residence time.

Table I – Parameters used in the Simulated Cooling Scenarios

| Parameter | Value | Reference |
|------------------------------------|--|-----------|
| Initial temperature T_{ini} | 1100 °C | |
| Quench bath temperature, T_{inf} | 50 °C | |
| Thermal conductivity, k | 30 W / m - °K | [19] |
| Thermal diffusivity α | 7.003×10^{-6} m ² /s | [19] |
| Specific heat C_p | 560 J / kg - °K | [19] |
| Density, ρ | 7650 kg / m ³ | [19] |
| Quench convection coefficient, h | 10 000 W / m ² - °K | [20] |
| Quench fluid velocity / flow rate | 847 L/m ² -s | [21] |

It should be emphasized that constant convection coefficients, constant thermal properties, and constant heat-transfer medium temperatures selected from literature (shown in Table I) were adopted to model the processes, and the latent heat of phase transformations was neglected for this simple study. In reality, a heat transfer process such as quenching is more complex, controlled by sample geometry, quench medium, agitation, fluid properties, steel properties, and the surface roughness^[22, 23]. The convection coefficient is known to vary during water quenching according to the formation of a vapor blanket, boiling, and convective stages. Furthermore, the thermal properties, including density, conductivity and specific heat, are known to vary with microstructural phase, composition and temperature. Thus, the current study is considered to represent a first approximation to real quenching and furnace partitioning processes.

RESULTS AND DISCUSSION

Water Quenching Model Results

To investigate the first step of the Q&P process, temperature histories and thermal gradients produced under various quenching scenarios were examined through several modeling case studies. Three plate thicknesses were each simulated for three different quenching processes, air cooling, water spray quenching and severe water quenching^[15]. Thermal gradients during quenching are greatest using more aggressive quenching, as expected, presenting the greatest challenge from the standpoint of understanding Q&P microstructure evolution and designing effective plate Q&P processing strategies. Calculated thermal histories for severe water quenching are summarized in Figure 3 for 6 mm, 18 mm and 50 mm plates for the center, surface and quarter point locations through the thickness over quenching times up to 300 s (5 min).

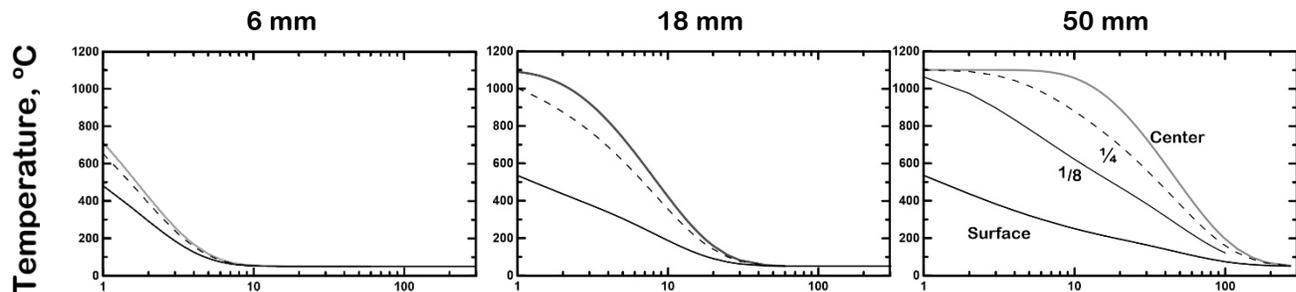


Figure 3. Thermal histories for 6, 18 and 50 mm thick steel plates cooled from 1100 °C via severe water quenching. Time is shown on a log scale from 1 to 300 s. Thermal histories at the plate center position are indicated with a grey line; quarter thickness position by a dashed line; one-eighth thickness position by a thin line and at the surface by a bold line.

The cooling rate (°C/s) at a given time and position in a given plate is the slope of the temperature history shown in Figure 3. At early quenching times, the plate surfaces cool much more rapidly than the plate centers, with the surface temperature dropping significantly during the first 1s. However, at longer times, the surface cooling rates decrease and are eventually exceeded by the center cooling rates. The rapid surface cooling at early times is driven by the difference in temperature between the plate surface and the cooling media; conduction and convection scales with temperature difference, so a larger difference in temperature will cause more rapid heat extraction. At longer quench times, the conductive heat transfer from plate center to plate surface exceeds the convective heat transfer from plate surface to quench media, so the interior cools faster.

The difference between surface and center cooling rates depends greatly on plate thickness. Steeper thermal gradients (indicated as greater differences in temperature between the surface and center positions) develop in the thick plates. The surface and near-surface lose heat very rapidly, while the plate center retains heat for longer times. For example, the center of the severely quenched 50 mm plate remains at the initial temperature of 1100 °C for 10 s.

Application of Cooling Profiles to Q&P Processing Response

In the context of the Q&P process, the cooling rates during initial quenching are important, because they control any diffusional phase transformations during quenching and define the “hardenable” requirements for the steel, and thus the alloying requirements. Severe water quenching allows the hardenable alloying additions to be minimized at a given plate thickness, or the maximum plate thickness to be maximized for a given alloy. The temperature gradients after initial quenching are also important, because the lowest temperature reached at the end of the quench step largely controls the initial martensite phase fraction, which, in turn, influences the final phase fractions. To generate classic Q&P microstructures, the quench step must meet two important criteria. First, the cooling rate at every position through the thickness should be sufficient to avoid intermediate diffusional transformation products, such as ferrite and cementite in pearlite or bainite, and second, the temperature at every position through the thickness after quenching should form a controlled amount of martensite to allow austenite stabilization during partitioning. Thermal gradients present a difficult microstructural challenge, and have not been previously developed in the context of Q&P process design.

Thermal Gradient Effects on Through-Thickness Microstructural Variation after Quenching

The effect of thermal gradients on the expected phase distribution after the quenching step can be estimated from the quenching model results using the Koistinen and Marburger equation which defines the extent of martensite transformation from austenite based on the undercooling below the M_s temperature. The thermal histories in the 18 mm plate during the first 20 s of severe water quenching are considered here as an example (Figure 4). For this example, the same 0.2 wt. pct. carbon hypothetical steel with an M_s temperature of 400°C was assumed, as in Figure 2 above. The M_s temperature and the “optimum” quench temperature are shown as horizontal lines in the figure; these are important points of reference in relation to the martensite transformation behavior during quenching.

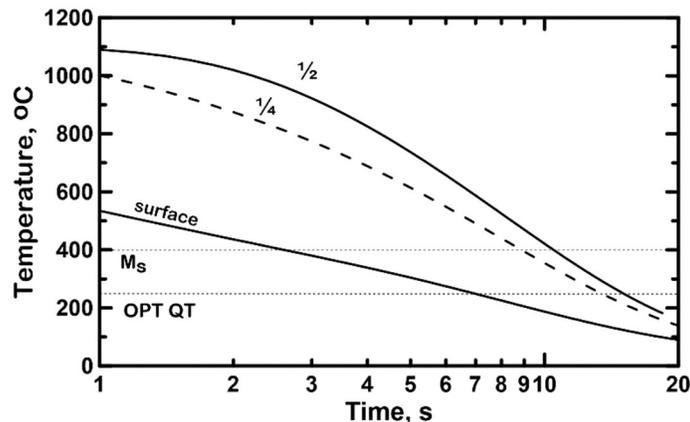


Figure 4. Simulated thermal history for severely water quenched 18 mm plate from 1100°C for 20 s. M_s (400 °C) and optimum QT (~250°C) indicated for a 0.2 wt. pct. C steel.

Examining the thermal histories at the different through-thickness positions shown in Figure 4, in the context of the martensite transformation behavior for this example steel, the plate surface reaches the M_s temperature in ~2 - 3 seconds, while the plate center does not reach M_s until 10 s. Thus, the phase distributions change rapidly during the first 20 s of severe water quenching of this 0.2 wt. pct. C steel. The 300 s quenching time modeled in Figure 3 would be far too lengthy for this plate, as the plate would be cooled far below the optimum quench temperature. The fractions of martensite and untransformed austenite can be estimated at any position of the plate at any time during quenching, and making the assumption of ideal partitioning, the fractions of partitioned martensite, retained austenite, and “fresh” martensite after final cooling to room temperature can also be estimated.

Figure 5 shows the predicted phase fractions for quenching times of 6s, 10s and 20s during severe water quenching of the 18 mm thick plate at the initial quench temperature, and assuming an idealized partitioning step followed by final cooling to room temperature. The phase fractions in the microstructure are plotted against the initial quench temperature achieved during cooling, consistent with the model from Figure 2 above. The plate surface, eighth point, quarter point and center positions are indicated in each figure; the surface having the lowest initial QT and the center having the highest initial QT. In each case there

is a greater fraction of martensite at the quench temperature nearer the surface, as expected, due to the greater undercooling below M_s . After idealized partitioning and final quenching, the microstructure distributions are more complicated and the final microstructure gradients are substantially different for different quench-stop times.

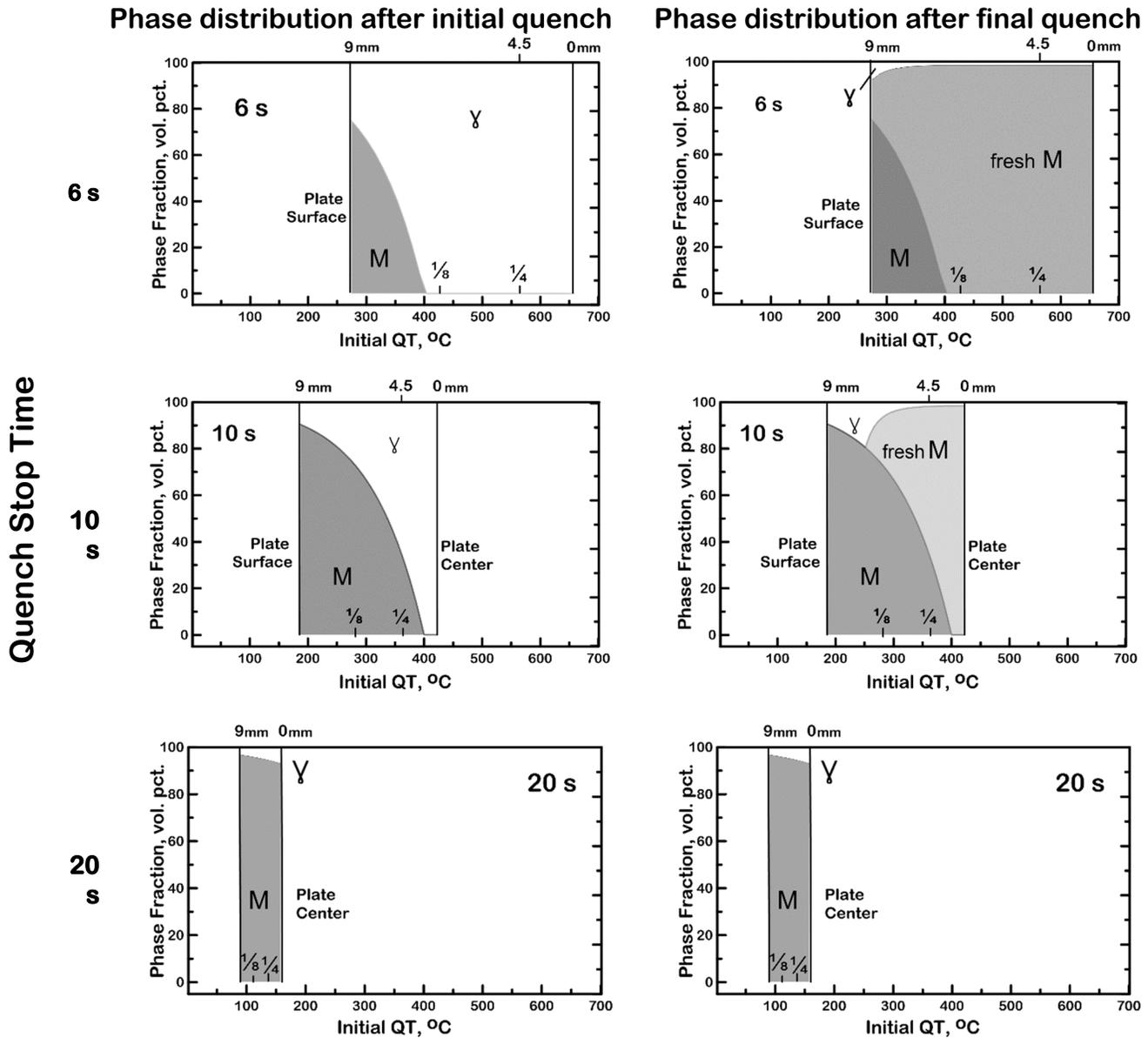


Figure 5. Estimated phase fractions through the thickness of an 18 mm plate severe water quenched from 1100°C as a function of initial quench temperature, after quenching (left) for times of 6, 10 and 20 s. Estimated final phase fractions after cooling to room temperature (following full partitioning) as a function of initial quench temperature (right). Phase fractions are shown for a 0.2 wt. pct. C alloy with an M_s of 400 °C. Martensite is indicated by M, austenite by γ , and martensite formed during final cooling by fresh M.

After quenching for 6 s, Figure 5 shows that a small region at the plate surface has transformed to 75 vol. pct. martensite, while the remainder of the plate is fully austenitic. After 10 s, the plate surface has just reached M_s so that the microstructural gradient ranges from 0 vol. pct. martensite at the center, to greater than 90 pct. at the surface. After 20 s, every location within the plate, from center to surface, contains above 85 vol. pct. martensite.

The final phase distributions, estimated on the right in Figure 6, also vary considerably with quench time. After a 6 s quench, an idealized partitioning treatment and a final quench to room temperature, the plate microstructure is dominated by fresh

martensite, except near the plate surface where some austenite is retained. For this cooling time, most of the plate was untransformed during quenching, so the desired conditions for effective Q&P processing (partial martensitic transformation during quenching) were not realized. After an initial 10 s quench, up to a fifth of the plate (within approximately 2 mm of the surface) contains greater than 10 wt. pct. retained austenite. The final microstructure gradient is dominated by partitioned martensite at the surface, fresh martensite at the center, and the greatest austenite fraction at a location near the eighth point position. After a 20 s quench time, the entire plate consists of partitioned martensite plus a small fraction of retained austenite, and no fresh martensite is formed on final cooling as the temperature after quenching is below the optimum QT at every location through the thickness.

This illustration of phase distribution variations due to thermal gradients shows the importance of the quenching step in controlling the amount of austenite that can be stabilized during partitioning. The maximum retained austenite content is achieved at locations where the quench temperature corresponds to the optimum QT, which can be controlled via the quench stop time. The quench stop time is therefore an important processing parameter and must be tailored to the selected alloy, thickness and cooling process. The methodology presented herein provides a means to predict the response to processing, and thus should enable quenching process design for Q&P plates.

Furnace Partitioning

It is important to acknowledge that the analysis leading to Figure 5 assumed idealized full partitioning, and industrial Q&P process design also needs to incorporate a partitioning model which quantifies the extent of partitioning encountered during furnace heating for different realistic furnace temperatures and holding times. Such a partitioning model is described in this section, using the example of an 18 mm plate, severely water quenched, and partitioned assuming a process that involves reheating and holding in a tempering furnace held at 600°C.

The calculated thermal history including both quenching and furnace reheating is illustrated in Figure 6.

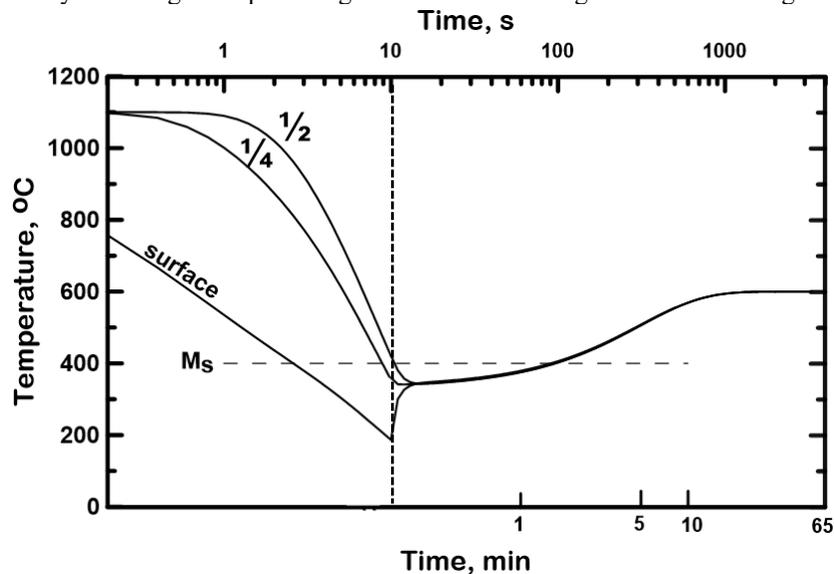


Figure 6. Thermal history through the thickness of an 18 mm plate, severe water quenched from 1100°C, then reheated in a furnace at 600°C. Surface, center (mid-thickness) and quarter point locations are shown. The quench-stop time is indicated by the dashed vertical line, and an assumed M_s temperature is shown for reference with the dashed horizontal line. The time represents the total elapsed time from the onset of quenching.

Figure 6 applies to a quench-stop temperature of 10 s (indicated by the dashed vertical line), where furnace reheating begins. A different quench stop temperature would be associated with a different temperature distribution through the thickness at the onset of partitioning. Because of the great variation of temperature in the plate at the onset of furnace reheating, the half- and quarter-thickness locations continue to experience rapid cooling, while the surface experiences rapid reheating. In the first few seconds of reheating, the temperature profile through the plate thickness is dominated by “equilibration,” virtually eliminating the through-thickness temperature gradient after a short time (plate surface and center temperatures match within 4 °C after 10 s, and within 1° C after 5 minutes of furnace time). Continued holding in the reheating furnace involves slow heating, with the plate uniformly reaching the furnace temperature of 600°C after about 1000 s. For this plate thickness, while the temperature

varies considerably during quenching, leading to microstructure variations prior to partitioning, the temperature equilibration during the first few seconds of reheating should cause the partitioning response to be quite uniform through the thickness.

The non-isothermal partitioning model described earlier was applied to the calculated thermal profiles during the reheating step following quenching in Figure 7, *i.e.* with partitioning beginning at an elapsed time of 10 s in Figure 6. The tempering parameter, which represents time at temperature, increases with time during the partitioning step, as expected. The TP values are greater in the (hotter) center for the first 20-30 s, and then the evolution of the tempering parameter is quite uniform through the thickness with continued furnace holding. The model presented in Figure 7 enables the partitioning response to be evaluated for any plate, knowing the initial temperature distribution after quenching, and the furnace temperature and holding time. A preferred partitioning response (*i.e.* a preferred value of the Hollomon-Jaffe tempering parameter) can be selected based on extensive experience with isothermal partitioning in Q&P steels, and in conjunction with the quenching model, should enable considerable progress in Q&P processing and microstructure design for plates steels. Follow up research continues to verify experimentally the process design concepts presented here.

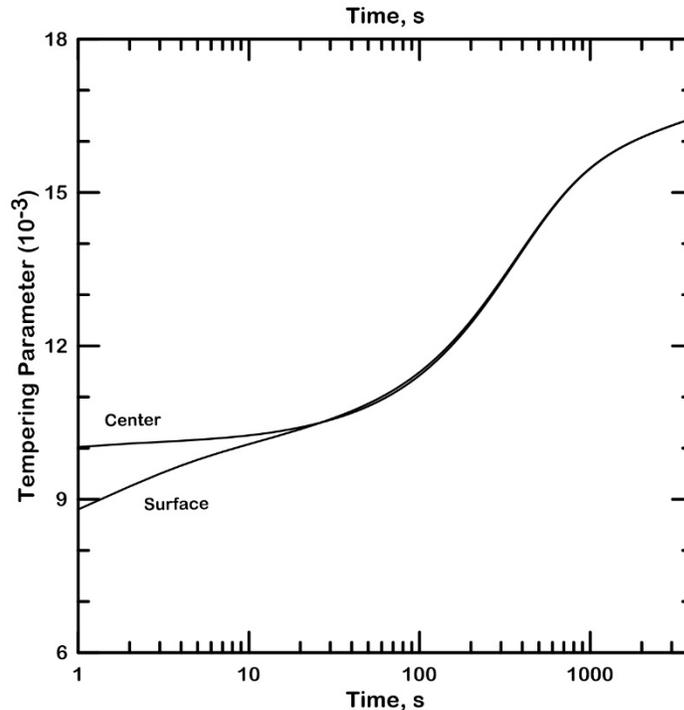


Figure 7. Evolution of tempering parameter (TP) during partitioning in a 600 °C furnace, for an 18 mm plate severe water quenched for 10 s. Surface and center locations are shown. The time represents the total elapsed time from the completion of water quenching.

CONCLUSIONS

While past research in quenching and partitioning (Q&P) has mostly focused on sheet steels with isothermal partitioning, the range of cooling rates and thermal gradients which develop in thick sections during processing of plates presents a new challenge in obtaining Q&P microstructures. Understanding the thermal history at each location through the plate thickness is essential to controlling microstructural variations. A modeling procedure has been developed to study the thermal histories at each location during both the quenching and furnace partitioning steps. Microstructure evolution under idealized partitioning conditions has been illustrated using the example of a severely water quenched 18 mm thick plate, for a hypothetical 0.2 wt. pct. C steel with an M_s temperature of 400 °C. The microstructure gradients associated with quench temperature variations are illustrated, emphasizing the importance of the quench-stop time. A non-isothermal partitioning model was then developed and applied to the furnace reheating thermal histories, following a method developed by Thomas *et al.* [9]. The model predicts the extent of partitioning based on the Hollomon-Jaffe tempering parameter, and in combination with the quenching model, provides a powerful tool for the design of plate Q&P microstructures and processes.

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