

Quenching and Partitioning of Plate Steel: Thermal Gradients and Microstructure Development During Quenching

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INTRODUCTION

The third generation of advanced high strength steels (AHSS) is a class of sheet steels characterized by mixed microstructures containing retained austenite (RA) [1]. Such microstructures provide excellent combinations of strength, ductility, formability and toughness, which are of interest to the automotive industry [2]. Such microstructures have also shown promise in wear applications [3, 4]. Quenching and partitioning (Q&P) proposed by Speer *et al.* [5], has been commercialized as a heat treatment for low-alloy sheet steels, to produce third generation AHSS microstructures and properties.

The Q&P process, shown in the processing schematic in Figure 1, has two steps. An initial quenching process, designed to reach a specific initial quenching temperature where a desired martensitic fraction is formed, and a partitioning process designed to allow a substantial portion of the carbon in the martensite to diffuse into the austenite, while minimizing loss of carbon to cementite or transition carbide precipitation. The increased carbon stabilizes the retained austenite, which in turn provides increased ductility and toughness to the final microstructure. A final quench to room temperature completes the process. These precise microstructural processes and targets place stringent demands on process control during both steps. Q&P literature based on sheet processing cites the quench temperature (QT), partitioning temperature (PT) and partitioning time (Pt) as important parameters that should be carefully controlled [5, 6].

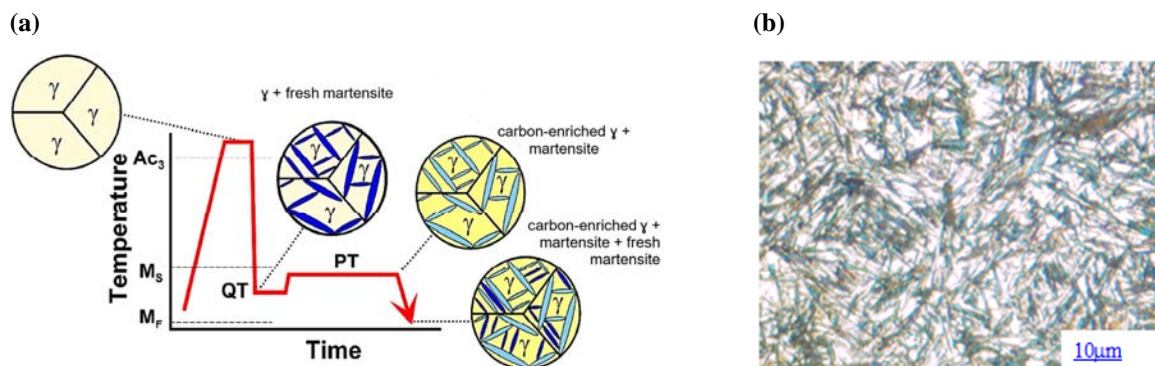


Figure 1. (a) Schematic of 2-step Q&P sheet thermal processing, with full austenitization. QT and PT are quenching and partitioning temperatures, respectively. M_s and M_f are the martensite start and finish temperatures. Expected microstructures at each step are illustrated [7]. (b) Light Optical Micrograph of 9260 Q&P: 190 °C-400 °C-10 s, tint etched using picral, then sodium metabisulfite, retained austenite (white) and partitioned martensite (dark) [8].

Reaching the desired QT is critical to martensite formation during the quenching step and balancing the subsequent partitioning times and temperatures are critical to maximize retained austenite contents. The optimum QT is defined as the temperature at which RA, after idealized (full) partitioning, will have an M_s below room temperature, thus minimizing or precluding the formation of fresh martensite on final cooling [5]. The optimum QT can be estimated by application of the Koistinen and Marburger (K-M) equation (Equation 1), where V_m is volume of martensite, K is a constant with a typical value of 0.011 and M_s is the martensite start temperature which can be estimated according to empirical functions, such as Equation 2, proposed by Andrews [9], or measured directly, using dilatometry.

$$V_m = 1 - e^{-K(M_s - QT)} \quad (1)$$

$$M_s = 539 - 423C - 30.4Mn - 17.7Ni - 12.1Cr - 7.5Mo \quad (2)$$

For a given quench temperature, if full partitioning is assumed to take place, the carbon content of the retained austenite can be estimated using the lever rule. The M_s of the untransformed austenite is recalculated (Equation 2) taking into account the updated carbon content. Equation 1 is again used to estimate the fraction of austenite that transforms to martensite upon final cooling to room temperature. Using this methodology, the fraction of partitioned martensite, untransformed austenite and 'fresh' martensite can all be estimated in the final microstructure.

Figure 2 illustrates the estimated retained austenite fraction after partitioning and cooling to room temperature versus the QT prior to partitioning for a 0.2C (wt. pct.) steel with a M_s temperature of 400 °C. For this steel, the optimum QT is 250 °C, which corresponds to a retained austenite content of 19 vol. pct.

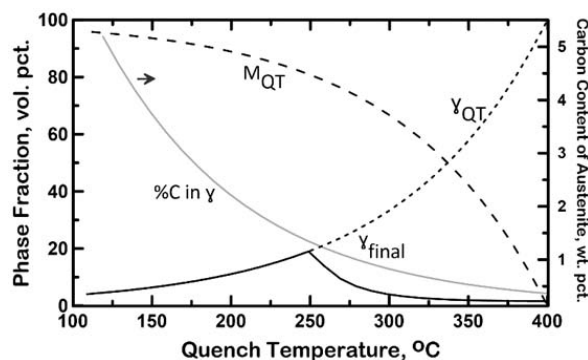


Figure 2. Calculated phase fractions as a function of initial quench temperature in a hypothetical Q&P process with full partitioning. Phase fractions calculated for a 0.2C steel with $M_s = 400$ °C. M_{QT} and γ_{QT} correspond to the amount of martensite and austenite present after quenching to QT.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

It should be noted that the application of Equation 1 assumes compositional and microstructural homogeneity following an interrupted quench step and a reheating step. The maximum estimated retained austenite has rarely been attained in previous Q&P experiments, likely due to competition from reactions such as carbide precipitation [10, 11]. In addition, the maximum experimentally achieved retained austenite has not always corresponded to the estimated optimum QT for that partitioning treatment [9].

This QT selection methodology is widely used [12, 13, 14, 15] to select a range of QT for experimental work. A range of PT and Pt have also been used in experimental Q&P studies and a variety of Q&P microstructures have been produced; the amounts, morphology and distribution of phases change with alloying and processing [6, 10, 16]. Experimental Q&P studies have explored one-step [8, 17, 18] and two-step [6, 7, 11] processes through Gleeble simulation or dilatometry, as well as laboratory production of hot and cold rolled Q&P sheet [16, 19, 20]. A study by Thomas [21] developed the concept for Q&P hot-rolled sheet production, using coil cooling as the partitioning step. 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 [21], due to cooling rate variations.

The Q&P process has been commercialized for sheet steels, where thermal gradients through the thickness are small. A handful of studies have considered the possibility of applying Q&P in steel plate [22–24]. Hong *et al.* obtained Q&P microstructures with interesting properties in laboratory heat treated plate, thus suggesting the opportunity for thick plate Q&P [22]. Zhou *et al.* examined temperature and microstructural gradients in hot rolled plate through thermal modeling and experimental validation [23]. 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 almost the same microstructures (martensite laths) throughout the cross section.

The above studies suggest that microstructural variations may arise through the thickness in Q&P processing of plates, due to variation in cooling rates and thermal gradients. Unlike sheet Q&P processing, thermal gradients are important to consider in Q&P processing of thick plate. Q&P literature based on sheet processing cites the quench temperature (QT), partitioning temperature (PT) and partitioning time (Pt) as important parameters to be controlled. In plate Q&P, these parameters are less defined; a range of QT-PT-Pts and therefore a range of microstructures will exist through the thickness. Control of microstructure and properties in Q&P plate therefore requires an understanding of the evolving thermal gradients. The influence of varying through thickness thermal histories on the Q&P process has not been systematically studied with the goal of commercially producing Q&P microstructures in thick plate. Thermal gradients induced during processing change with time, plate thickness and process parameters, and are therefore difficult to predict or measure experimentally for the wide range of thicknesses and processes of interest. 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 and reheat mediums on temperature profiles and thus, expected microstructure development.

This work focuses on the development and application of a thermal model to investigate thermal gradients induced during plate Q&P processing. The cooling profiles produced under various thickness and process conditions are simulated and the effects of thermal gradients on final microstructures are investigated. Final phase fractions are estimated by applying methods developed in sheet Q&P to the simulated plate thermal profiles.

THERMAL MODELING TOOL

Model Formulation

A simple finite-difference model was developed to simulate temperature evolution during the cooling of a flat steel plate. For a typical flat plate shown in Figure 3 (a), 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 solutions to this partial differential equation provide the variation of temperature with both time and position in the plate. In the absence of internal heat generation, and assuming constant thermal properties, Fourier’s equation is:

$$\frac{dT}{dt} = \alpha \left(\frac{d^2x}{dt^2} + \frac{d^2y}{dt^2} + \frac{d^2z}{dt^2} \right) \quad (3)$$

where T is temperature, t is time, x , y and z are distances in the thickness, width and length directions respectively, and α is thermal diffusivity, defined as:

$$\alpha = \frac{k}{\rho C_p} \quad (4)$$

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. Assuming identical boundary conditions at the plate top and bottom surfaces creates a symmetry plane at the plate center, as shown in Figure 3 (a). Ignoring variations near the plate ends and sides due to edge cooling, and assuming uniform heat transfer to the surface, this transient conduction problem simplifies to a single dimension, given by Equation 5, and can be solved either analytically or numerically.

$$\frac{dT}{dt} = \alpha \frac{d^2x}{dt^2} \quad (5)$$

The finite-difference model solution to Equation 5 can be approximated numerically as Equation 6, by discretizing the domain into cells with nodes as shown in Figure 3 (b), and performing an energy balance around each cell.

$$\frac{\Delta T}{\Delta t} = \frac{T_i^{t+1} - T_i}{\Delta t} \quad (6)$$

The notation in Equation 6 includes a temperature term with indices for position and time: $T_{position(x)}^{time(n)}$

Expressions for temperature were obtained for each cell (Equations 7 through 9). The surface cell where the convection boundary condition is applied, is 'cell n'; the center cell, where the insulated boundary condition is applied, is 'cell 1', and the other cells comprising the interior are 'cell i'. The number of nodes ($n = 50$ nodes) was established based on a mesh size study.

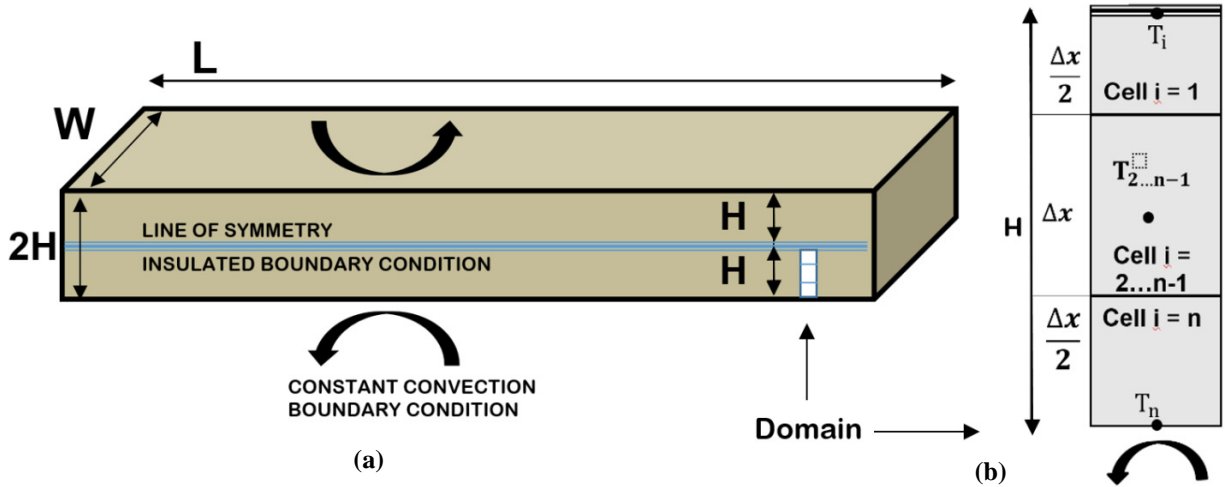


Figure 3. (a) Flat plate geometry where thickness, $2H$, is much less than the length, L , and width, W . Symmetric boundary conditions of constant convection at plate surfaces are illustrated with curved arrows. Modeled domain is a 1D slice of half the plate thickness. (b) Close-up of the discretized domain showing cells, nodes and dimensions.

$$T_1^{t+1} = T_1^t + \frac{2k\Delta t}{\rho C_p \Delta x^2} [T_2^t - T_1^t] \quad (7)$$

$$T_i^{t+1} = T_i^t + \frac{k\Delta t}{\rho C_p \Delta x^2} [T_{i-1}^t - 2T_i^t + T_{i+1}^t] \quad (8)$$

$$T_n^{t+1} = T_n^t + \frac{2k\Delta t}{\rho C_p \Delta x^2} [T_{n-1}^t - T_n^t] + \frac{2h\Delta t}{\rho C_p \Delta x} [T_\infty - T_n^t] \quad (9)$$

A transformed version of Equations 7 through 9 was written in MATLAB (Equations 10 through 12), and solved using the built-in MATLAB ordinary differential solver (ODE45) which uses a Runge-Kutta fourth-order approximation.

$$\frac{dT}{dt_1} = \frac{2k}{\rho C_p \Delta x^2} (T_2 - T_1) \quad (10)$$

$$\frac{dT}{dt_i} = \frac{k}{\rho C_p \Delta x^2} (T_{i-1} - 2T_i + T_{i+1}) \quad (11)$$

$$\frac{dT}{dt_n} = \frac{2k}{\rho C_p \Delta x^2} (T_{n-1} - T_n) + \frac{2h}{\rho C_p \Delta x} (T_\infty - T_n) \quad (12)$$

This numerical model was validated against an analytical model built in Microsoft Excel®, using a 20-term series^[25] to solve a simple problem of transient quenching of a 24 mm thick plate. The numerical model matched the analytical model within 0.001 pct. maximum error at any of the 50 nodes, which verifies the numerical method.

The model was then applied to investigate a wide range of quenching scenarios and plate thicknesses, assuming constant steel properties, (invariant with both temperature and microstructure), given in Table 1. A constant convection coefficient (that included radiation) and constant quench medium temperature selected from literature was adopted to represent each of three quenching processes. The latent heat of phase transformation was neglected for this simple study. In reality, quenching is a complex heat transfer process controlled by sample geometry, quench medium, agitation, fluid properties and workpiece thermal properties^[26, 27]. The convection coefficient is known to vary during quenching according to the 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 represents a first approximation to the real quenching processes.

Thermal Modeling Case Studies

To investigate the first step of the Q&P process, the temperatures and thermal gradients produced under various quenching scenarios were examined through nine modeling case studies. Three plate thicknesses (6, 18 and 50 mm) were each simulated for three different quenching processes, starting from an initial temperature above A_{c3} , of 1100 °C. The three cooling processes of air cool, water spray quench and severe water quench were chosen to represent a wide range of potential process scenarios^[28]. Approximate convection coefficients appropriate for each cooling process were selected from literature^[29, 30]. The value chosen for air cooling includes some forced convection, so the internal thermal gradients, cooling rate, and temperature variations for natural convection cooling would be even smaller than the results shown here. Cooling media temperatures were fixed at 50 °C. Process parameters and material properties used in the simulations are shown in Table I.

Table I – Parameters used in the Simulated Cooling Scenarios

| Parameter | Value | Reference |
|------------------------------------|---|-----------|
| Thickness, 2H | 50 mm; 18 mm; 6 mm | |
| Modeled half thickness, H | 25 mm; 9 mm; 3 mm | |
| Initial temperature T_{ini} | 1100 °C | |
| Quench bath temperature, T_{inf} | 50 °C | |
| Thermal conductivity, k | 30 W / m - °K | [30] |
| Thermal diffusivity α | 7.003×10^{-6} m ² /s | [30] |
| Specific heat C_p | 560 J / kg - °K | [30] |
| Density, ρ | 7650 kg / m ³ | [30] |
| Quench convection coefficient, h | 100 W / m ² - °K; 1000 W / m ² - °K; 10 000 W / m ² - °K | [28] |
| Quench fluid velocity / flow rate | 40 m/s; 13 L/m ² - s; 847 L/m ² -s | [29] |
| Number of nodes | 50 | |

RESULTS AND DISCUSSION

Thermal Model Results

Results of the nine cooling scenarios are presented as temperature-time plots in Figure 4. The thermal histories at three positions through the thickness are shown for the 6 mm and 18 mm plates: center, surface and quarter point. Four locations are shown for the 50 mm plate: center, surface, quarter point and eighth point. Thermal histories are shown for quench times up to 300 s, or 5 min. Note that the temperature change with respect to distance is referred to as the thermal gradient and the temperature change with respect to time is referred to as the cooling rate.

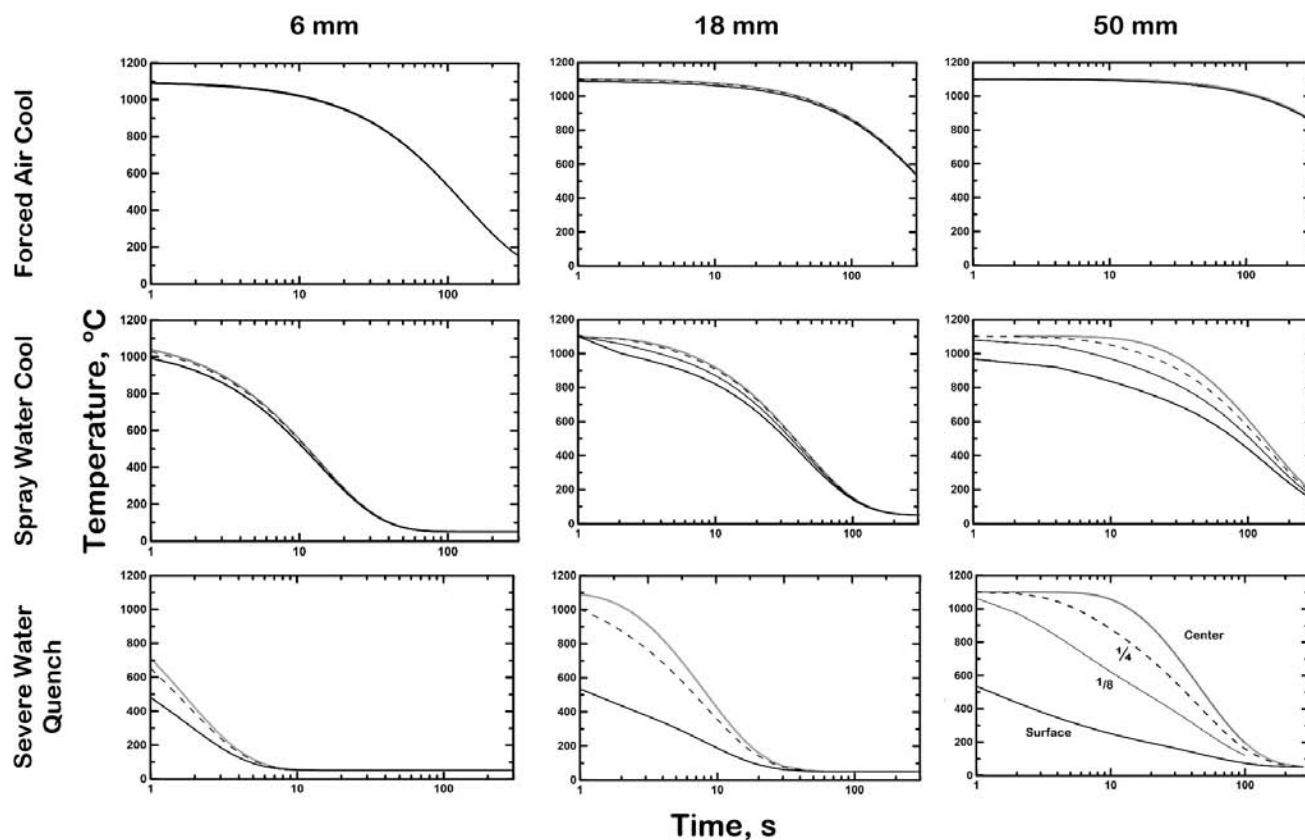


Figure 4. Thermal profiles for plate thicknesses 6, 18 and 50 mm quenched from 1100 °C using three quenching media: severe water quench (convection coefficient, $h = 10\,000\text{ W / m}^2 \cdot ^\circ\text{K}$), spray water cool ($h = 1000\text{ W / m}^2 \cdot ^\circ\text{K}$) and air cool ($h = 10\text{ W / m}^2 \cdot ^\circ\text{K}$). Time is shown on log scale from 1 to 300 s. Thermal profiles at plate center are indicated with a grey line; quarter thickness position by a dashed line; one-eighth thickness position by a thin line and surface by a thick line.

Comparing the temperature-time thermal profiles in Figure 4 from left to right, the effect of thickness on thermal gradients and cooling rates can be examined. Comparing the profiles from top to bottom, the effect of quenching medium on the thermal gradients and cooling rates in a plate can be examined.

The cooling rate ($^\circ\text{C/s}$) at a given time and position in a given plate is the slope of the temperature history shown in Figure 4. At early quenching times, the plate surfaces cool much more rapidly than the plate centers. However, at longer times, the surface cooling rates may be exceeded by 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 (the ΔT term in Equation 6); 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 extent of the difference between surface and center cooling rates depends greatly on thickness and quench severity. Under air cooling, heat extraction at the plate surfaces is slow, and the plate cools at a near uniform rate through the thickness. Air cooling in the 6 mm, 18 mm and even 50 mm plates is uniform from surface to center, as illustrated by the overlapping thermal histories. Quench severity greatly increases the surface cooling rates in all plate thicknesses, as expected, but quench severity does not increase the center cooling rates in all thicknesses. In the case of the 6 mm plate, the center cooling rate increases by an order of magnitude with increasing quench severity. In contrast, the cooling rate at the center of the thicker plates varies very little between quenching processes, as the center is insulated from the convection applied at the surface. Consequently, steep thermal gradients develop during spray water cooling and severe water quenching of the thick plates. The surface and near-surface lose heat very rapidly, while the plate center retains heat for longer times. As illustrated in Figure 4, the center of the severely quenched 50 mm plate remains at the initial temperature of 1100 °C for 10 s. In summary, through-thickness variations in temperature, temperature gradient, and cooling rate all increase with increasing plate thickness, and with increasing quench severity.

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, which would reduce the extent of martensite formation. The temperature

gradients after initial quenching are 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. Second, the temperature at every position through the thickness after quenching should form a controlled amount of martensite to allow austenite stabilization during partitioning.

The criteria for cooling rate will be examined first. Then, the effects of thermal gradients on Q&P microstructures will be examined in some depth. Thermal gradients present a difficult microstructural challenge, and have not been previously considered in the context of Q&P.

Importance of Cooling Rates During the Initial Quench Step of Q&P

Ideally, the cooling rate at every position through the plate thickness should be sufficient to form only martensite during quenching. Critical cooling rates, often reported in the range of temperatures between 800 and 500 °C, are alloy specific. Linear approximations of the cooling rates between 800 and 500 °C and the corresponding times to reach an M_s temperature of 400 °C are presented in Table II for each of the nine cases. These results should be helpful in selecting alloys with sufficient hardenability for any desired cooling condition.

Table II – Average Cooling Rates from 800 °C to 500 °C at Center and Surface for Each Quench Process and Plate Thickness

| Plate Thickness | Cooling Medium | Center °C/s | Surface °C/s | Time for Plate Center to Reach M_s 400 °C (min:sec) |
|-----------------|---------------------|----------------|-----------------|--|
| 50 mm | Severe Water Quench | 13 | 155 | 1:00 |
| | Water Spray Quench | 4 | 4 | 2:55 |
| | Air Cool | 0.5 | 0.5 | 20:02 |
| 18 mm | Severe Water Quench | 72 | 273 | 0:10 |
| | Water Spray Quench | 14 | 14 | 0:48 |
| | Air Cool | 1.6 | 1.6 | 7:09 |
| 6 mm | Severe Water Quench | 347 | 386 | 0:02 |
| | Water Spray Quench | 44 | 45 | 0:14 |
| | Air Cool | 5 | 5 | 2:21 |

Analyzing the cooling behaviors in Figure 4 with respect to Q&P processing, certain thicknesses may be more suitable than others for the different cooling processes. For example, air cooling may be impractical for thicknesses above 6 mm as cooling rates (less than 2 °C/s) may be too slow to form martensite and highly hardenable alloys would be required for thicker sections under air cooling conditions.

Spray water quenching and severe water quenching achieve shorter cooling times in the thicker sections (under 3 mins), although both introduce thermal gradients. Thermal gradients naturally increase with quench severity and thickness. Severe water quenching produces very steep thermal gradients: up to 700 °C variation in through thickness temperature in thick plate. Spray cooling shows promise for a controlled quench rate across a range of thicknesses where the cooling times are reasonable and thermal gradients are more modest.

Thermal Gradient Effects on Through-Thickness Microstructural Variation

The effect of thermal gradients on the expected phase distribution after quenching were estimated from the thermal model results using the Koistinen and Marburger equation (Equation 1). The thermal histories in the 18 mm plate during the first 20 s of severe water quenching are shown as an example. The thermal histories at the center, quarter point and surface positions are enlarged in Figure 5 for this example.

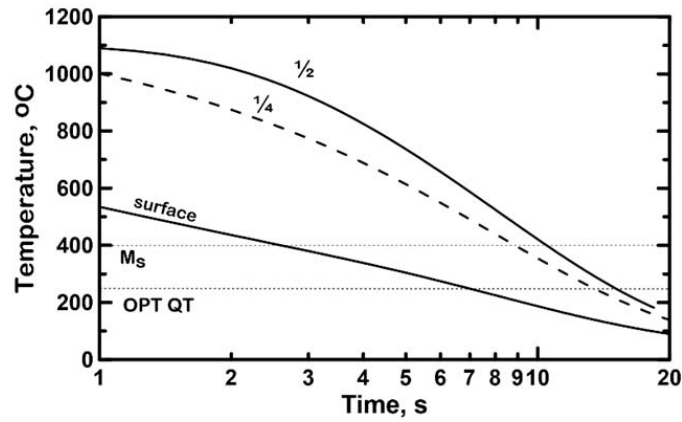


Figure 5. Simulated thermal history for severely water quenched 18 mm plate from 1100 °C for 20 s. M_s (400 °C) and optimum QT (~250 °C) indicated for a 0.2 wt. pct. C steel.

Examining the thermal histories shown in Figure 5, in the context of the transformation behavior for an alloy with an assumed M_s of 400 °C, the plate surface reaches an M_s of 400 °C 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. Assuming full partitioning, phase fractions after partitioning and final cooling to room temperature can also be estimated. The estimated phase distributions after initial quenching and final cooling, are illustrated in Figure 6. Figure 6 shows the phase fractions as a function of temperature at each position through the thickness, from surface to center, after quenching for five different times: 6, 8, 10, 15 and 20 s. Fractions of martensite and untransformed austenite are shown as a function of QT in the left column of Figure 6; final phase distributions after cooling to room temperature are shown on the right, including the fractions of retained austenite and fresh martensite.

Figure 6 shows the phase distributions estimated in the 18 mm plate after quenching for 6 s: a small region at the plate surface has transformed to 75 vol. pct. martensite, while the remainder of the plate is fully austenitic. After 8 s, the plate surface has transformed to 80 pct. martensite while the plate center has not reached M_s . 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 15 s and 20 s, the complete plate thickness from center to surface, contains above 75 vol. pct. martensite and 85 vol. pct. martensite, respectively.

Phase distribution after final quench

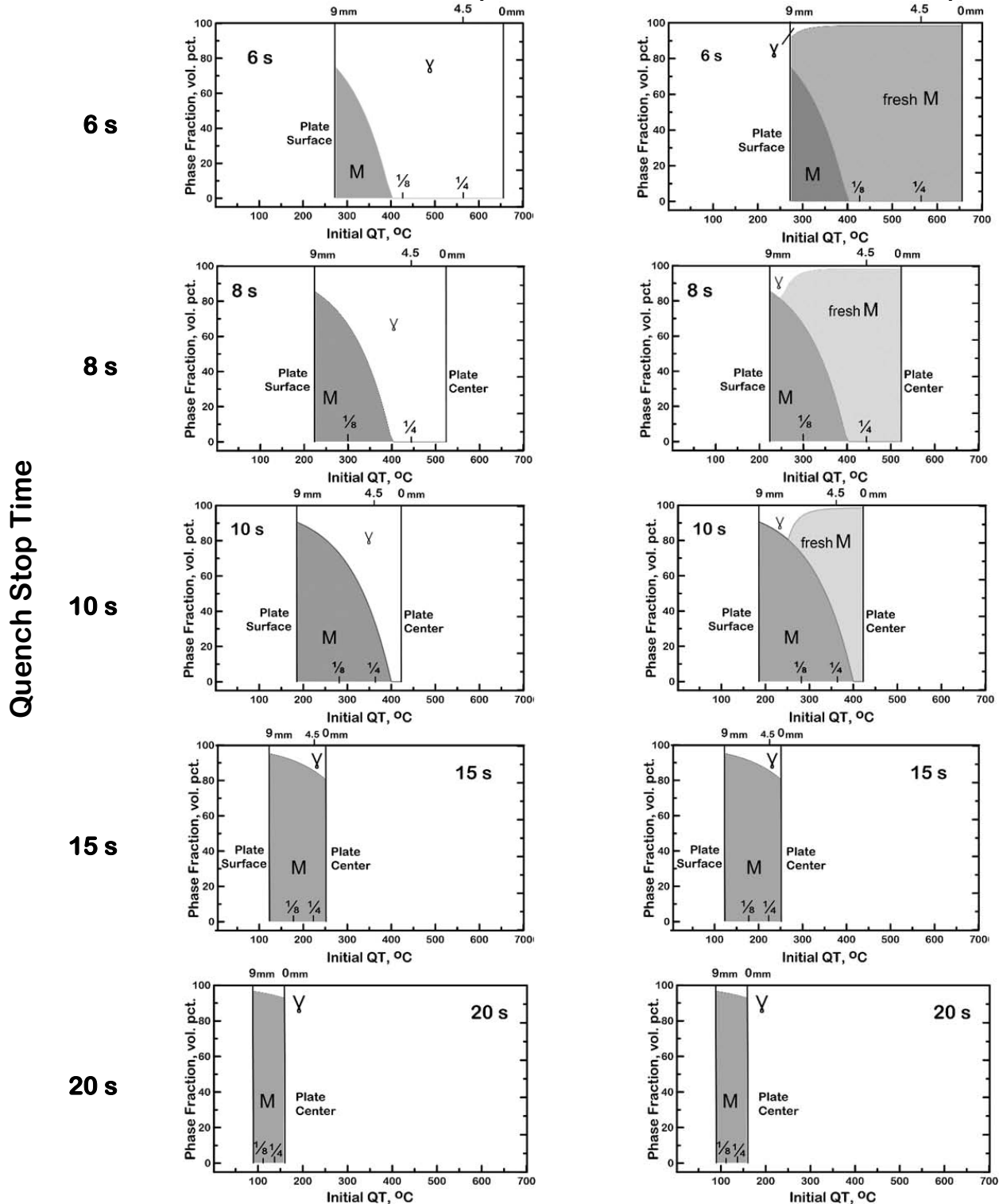


Figure 6. Estimated phase fractions through the thickness of an 18 mm plate severe water quenched from 1100°C as a function of initial quench temperature, after quenching for 6, 8, 10, 15 and 20 s. Estimated final phase fractions after cooling to room temperature (assuming full partitioning) as a function of initial quench temperature, for initial quench times of 6, 8, 10, 15 and 20 s. Phase fractions are shown for a 0.2 wt. pct. C alloy with an M_s of 400 °C. Martensite indicated with M, austenite indicated with γ , and martensite formed during final cooling indicated with fresh M.

The estimated final phase distributions, shown in the right hand column 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 is completely

martensitic, except for a small fraction of retained austenite (7 vol. pct.) at a depth of 0.1 mm below the plate surface. For an idealized partitioning treatment after an 8 s initial quench, the microstructure from plate surface to 1 mm in depth contains appreciable amounts of retained austenite: 15 vol. pct. at the surface, increasing to 19 vol. pct. at a depth of 0.4 mm beneath the surface, then decreasing to 5 vol. pct. at a depth of 1 mm. The remaining thickness of the plate contains less than 2 vol. pct. retained austenite. 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. A quench time of 15 s corresponds to the time at which the plate center reaches the optimum QT, so that no new martensite is formed at any location through the thickness on final cooling. A quench time of 15 s represents an important time for a severe water quench of this alloy: the maximum possible distribution (i.e. integrated over the cross section) of austenite is stabilized to room temperature during ideal partitioning. The retained austenite content varies from 1.2 vol. pct. at the plate surface to 19 vol. pct. at the plate center for this condition. After a 20 s quench time, no fresh martensite is formed on final cooling as every location through the thickness is below the optimum QT, however the corresponding austenite distribution does not reach the maximum of 19 vol. pct. at any location through the cross section. The plate center contains 7 vol. pct. retained austenite; the plate surface contains 3 vol. pct. retained austenite.

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 austenite content is retained at the location where the temperature corresponds to the optimum QT, which can be controlled with quench stop time. The quench stop time is therefore an important processing parameter and must be tailored to the selected alloy. A variety of quench stop time selection methods could be considered. This time could be selected to achieve a desired final phase distribution, or a specified phase fraction at a desired location through the thickness. However, controlling the phase fractions by keeping this time within a few seconds will require stringent process control. Nonetheless, the methodology presented here helps to predict the response to processing, and thus enables process design.

It is important to acknowledge that this analysis has assumed idealized partitioning. Heating profiles also need to be considered to incorporate the partitioning aspect of Q&P processing in a more substantial way. Partitioning of sheet steel is commonly conducted during a one-step hold, typically for short times (400 °C for 10 seconds is a common sheet partitioning treatment). Reheating of plate could perhaps be achieved through furnace reheating or induction heating. Induction heating after cooling is not commonly applied to plate production, but literature suggests that such a configuration has been used for tempering in one facility^[31]. As Q&P plate process design efforts continue, the influence of heating characteristics and thermal gradients will be further examined. The analysis provided here, focused on the initial cooling behavior, should already be quite helpful in Q&P process design, as it provides an estimate of the through-thickness distribution of phases in the final product, under idealized partitioning kinetics.

CONCLUSIONS

While past research in quenching and partitioning (Q&P) has mostly focused on sheet steels, the range of cooling rates and thermal gradients which develop in thick sections during processing present a new challenge in obtaining Q&P microstructures. Understanding the thermal history at each location through-the-thickness is essential to controlling microstructural variations. A thermal modeling tool was developed to study the cooling histories at each location during the quenching of different plate thicknesses with different quench process severities. The results were evaluated by adapting concepts from sheet Q&P to estimate the initial and final martensite phase fractions for a 0.2 wt. pct. C steel with an M_s temperature of 400 °C. For the design of the quench step, nine case studies were presented, examining three plate thicknesses under three cooling media. Air cooling produces uniform temperature distributions, and thus microstructures, although it may be impractical given the long times to reach typical Q&P QTs. Spray cooling shows promise for a controlled quench across a range of thicknesses where the cooling times are reasonable and thermal gradients are modest. Severe water quenching produces severe thermal gradients in the thicker plates. Microstructural variations through the thickness were estimated assuming idealized partitioning, so as to quantify thermal gradient effects on initial and final phase fractions. Quench stop time is an important parameter to select and control, in order to influence the final microstructure, according to the methodology developed here. This work will continue in future to incorporate industrial heating methods to investigate the partitioning step of Q&P process design.

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