HEAT TREATMENT PROCEDURE QUALIFICATION

Final Technical Report

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Heat Treatment Procedure Qualification for Steel Castings

Abstract

Heat treatment practices used by steel foundries have been carefully studied as part of comprehensive heat treatment procedure qualification development trials. These studies highlight the relationships between critical heat treatment process control parameters and heat treatment success. Foundry heat treatment trials to develop heat treatment procedure qualifications have shed light on the relationship between heat treatment theory and current practices. Furnace load time-temperature profiles in steel foundries exhibit significant differences depending on heat treatment equipment, furnace loading practice, and furnace maintenance. Time-temperature profiles of furnace control thermocouples can be very different from the time-temperature profiles observed at the center of casting loads in the furnace. Typical austenitization temperatures and holding times used by steel foundries far exceed what is required for transformation to austenite. Quenching and hardenability concepts were also investigated. Heat treatment procedure qualification (HTPQ) schema to demonstrate heat treatment success and to pre-qualify other alloys and section sizes requiring lesser hardenability have been developed. Tempering success is dependent on both tempering time and temperature. As such, furnace temperature uniformity and control of furnace loading during tempering is critical to obtain the desired mechanical properties. The ramp-up time in the furnace prior to the establishment of steady state heat treatment conditions contributes to the extent of heat treatment performed. This influence of ramp-up to temperature during tempering has been quantified.

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1.0 Introduction

Principles of heat treatment for steels have been well-studied and are well-understood. These principles provide the basis for heat treatment specifications and practices used by heat treaters and steel foundries on a daily basis. While current heat treatment specifications provide general guidelines for the heat treatment of steel castings, they do not address all critical aspects of steel casting heat treatment practice. A wide range of heat treatment equipment and heat treatment control strategies are used in today's steel foundries. Modern temperature data acquisition systems allow increased knowledge of the thermal conditions in a furnace load, not just in the furnace itself. This improvement in technology affords the possibility of load-based heat treatment time and temperature cycles, which are more precise than heat treatment cycles based on furnace temperature. Challenges in temperature monitoring of loaded furnaces have led to overly conservative practices to ensure complete heating of casting loads. Commonly used "hour-per-inch" rules are used to ensure that the centers of casting loads in heat treatment furnaces reach the appropriate temperature. However, these practices often result in holding castings at temperature far longer than is necessary.

For example, current heat treatment specifications for high alloy steels prescribe only the minimum heat treating temperatures and the quenching media. Variations in furnace conditions, furnace loading, quench delay, quench tank temperature, and quenchant velocity are not addressed in the current specifications. However, it is clear that these parameters must be carefully controlled to develop a successful heat treatment practice.

The use of heat treatment procedure qualification (HTPQ) methodologies can lead to the development of foundry-specific heat treatment practice guidelines to ensure heat treatment success over the broad range of heat treatment conditions that are likely to occur in a given foundry. Toward this aim, fully instrumented comprehensive HTPQ development trials have been conducted at three steel foundries. These in-plant trials and complementary Penn State laboratory heat treatment trials have served to assess the degree of heat treatment process control required for assurance of heat treatment success.

Current heat treatment practices used by steel foundries for carbon, low alloy and high alloy steels have been critically assessed based on the heat treatment literature, comprehensive HTPQ development trial results from steel foundries, and laboratory heat treatment trials. The applicability of heat treatment models from the literature has been assessed. From this assessment, critical components of steel casting heat treatment practice success have been identified. Also, robust HTPQ guidelines useful to both foundries and steel casting customers have been developed.

Heat treatment science is the basis from which most, if not all, of current heat treatment practices used in the steel foundry industry have been developed. However, a direct link between heat treatment science and practice often cannot be developed. For example, it is difficult, if not impossible, to link the kinetics of the ferrite to austenite transformation to a precise recommendation for furnace ramp-up and hold times during austenitizing of low alloy steel castings. Similarly, it is difficult to link austenite to martensite transformation kinetics information to precise recommendations for the minimum and maximum quench delays when transferring a basket of complex geometry castings into a quench tank. As a consequence, the need to develop robust heat treatment procedure qualification methods to ensure adequate heat treatment process control is paramount.

Penn State surveys have shown that significant differences exist in the current heat treatment practices used by SFSA member foundries. While most steel foundries use "hour-per-inch" guidelines to establish proper heat treatment times, the practice of this rule varies between foundries. For example, some foundries specify a fixed time in the furnace for their heat treatments. In this scenario, load variations can contribute to variations in actual ramp up times that result in significant variations in heat treatment hold times from load to load. Other heat treaters instrument the load itself during ramp up and use the temperature of the load to establish a sufficient heat treatment hold time. Critical issues such as this must be fully addressed before adopting short cycle heat treatments, which have been successful in some steel foundries but are not widely used [BRIG1958].

Heat treatment procedure qualification (HTPQ) methodologies offer the opportunity to develop robust heat treatment practices based on both fundamental principles and foundry-specific heat treatment practices. The comprehensive in-plant HTPQ development trials that are the foundation of this Penn State/SFSA research therefore serve two main purposes:

1. To develop simple robust HTPQ guidelines that can be used by foundries and casting customers for heat treatment quality assurance, and
2. To develop stronger links between fundamental heat treatment science and steel foundry heat treatment practice that can lead to better specification of heat treatment control limits.

Table I lists the key heat treatment process, practice and equipment variables that can be expected to influence heat treatment response. Process and equipment variables affect heat treatment response as do the selection of appropriate HTPQ set-points. Some of these key heat treatment response variables, such as the chemical composition and geometry, are inherent to the casting itself. For example, a low alloy composition has a lower hardenability, which requires a more aggressive quench to achieve full hardness when compared to richer alloy compositions. Furnace air circulation and quenchant circulation are dependent on the casting geometry. The “ranginess” or “compactness” of a casting can also affect the packing density of the heat treatment load.

Heat treatment equipment such as the furnace size and type can vary from foundry to foundry and can also vary from furnace to furnace within a foundry. The condition of the furnace door seal and the furnace insulation type strongly influences the time and temperature response of a furnace [CONN2001]. The time and temperature response of a furnace can also depend on the furnace controller. Temperature ramp-up is controlled either by the overall furnace capacity and load or by the furnace controller itself. Furthermore, the control of the furnace can also be affected by the type and location of the control thermocouple.

Table I: Comprehensive heat treatment variable list

Heat Treatment Variable	**Possible HTPQ Consideration**
Casting	
Grade	Grade/or Composition
Composition	Grade/Composition
Min. Section Size	Not Significant
Max. Section Size	Max. Section Size
Weight	Max. Section Size
Compactness/ Ranginess	Max. Section Size
Microstructure	Not Significant
Weld Repair	Not Significant
Prior Heat Treatment	Not Significant
Surface Condition	Not Significant
Heat Treatment Equipment	
Furnace Type	Heat Treatment Time and Temperature
Furnace Size	Heat Treatment Time and Temperature
Burner Location	Heat Treatment Time and Temperature
No. of Burners	Heat Treatment Time and Temperature
Insulation	Heat Treatment Time and Temperature
Burner Operating Characteristics	Heat Treatment Time and Temperature
Refractory Supports	Heat Treatment Time and Temperature
Door Seal Type	Heat Treatment Time and Temperature
Door Seal Condition	Heat Treatment Time and Temperature
Furnace Control	Heat Treatment Time and Temperature
Ramp-up Control	Heat Treatment Time and Temperature
Zone Control	Heat Treatment Time and Temperature
Cool-down Control	Heat Treatment Time and Temperature
Control T/C Location	Heat Treatment Time and Temperature
Control T/C Response	Heat Treatment Time and Temperature
Atmosphere	Not Significant
Hold Temperature Variation	Heat Treatment Time and Temperature
Heat Treatment Practice	
Set Temperature	Heat Treatment Temperature
Load Temperature	Heat Treatment Temperature
Ramp-up Time	Heat Treatment Time
Hold Time	Heat Treatment Time
Basket / Rack Geometry	Full load condition
Weight of Load	Full load condition
Density of Load	Full load Condition
Load Location	Full Load Condition
Initial Furnace Temperature	Heat Treatment Time and Temperature
Ramp / Hold Time Criteria	Heat Treatment Time and Temperature
Hold Time Variation	Heat Treatment Time
Quenching Equipment	
Quenchant Type	Quenchant Type
Tank Volume	Initial Quench Temperature
Make-up Water Conditions	Initial Quench Temperature
Pump Inlet / Outlet Locations	Initial Quench Temperature
Quench Practice / Control	
Quench Velocity	Quench Velocity
Delay Time	Delay Time
Initial Quench Temperature	Initial Quench Temperature
Initial Load Temperature	Not Significant
Load Volume	Full Load Condition
Load Surface Area	Full Load Condition
Quenched Hardness	Minimum As-Quenched Hardness
Final Casting Temperature	Final Quench Temperature
Casting Surface Condition	Not Significant
Localized Quench Velocity	Quench Velocity
Localized Quench Temperature	Final Quench Temperature
Normalizing	
Ambient Temperature	Not Significant
Air Velocity	Air Velocity
Air humidity (relative)	Less Significant
Load Volume	Full Load Condition
Load Density	Full Load Condition
Localized Air Velocity	Air Velocity
Localized Temperature	Air

Ultimately, it is the time and temperature response of the heat treated castings rather than the time and temperature of the furnace that controls treated properties. The "extent of heat treatment" includes not only time-at-temperature but also includes a component of the time-to-temperature, furnace ramp-up. This extent of heat treatment is different for different section sizes in a complex casting and for different castings within the heat treatment load. Castings in the center of a heat treatment basket in fully loaded furnaces can be expected to have significantly different time-temperature profiles than castings that are fully exposed in partially loaded furnaces.

The quenching system affects the ability of the heat treater to cool the casting uniformly and quickly. The effective quench severity experienced by a casting is influenced by many factors. The tank volume and quenchant type are critical. Make-up water to control temperature increases in the tank, as well as local quenchant velocities, influence the casting cooling rates. Quenching practice is as important as the quenching equipment. The delay time from the furnace to the quench tank must be short enough to prohibit unwanted microstructure transformations. The quench load size, density and casting surface condition will affect the local heat transfer coefficient at the casting-quenchant interface.

A successful HTPQ strategy incorporates critical heat treatment equipment, process and practice variables into a fundamental qualification framework without placing limits on less significant variables. It relies on demonstration of heat treatment success for HTPQ test conditions that mimic heat treatment process variable ranges commonly observed during production heat treatment. From the very long list of heat treatment variables shown in Table I comes a much shorter list of the most critical heat treatment parameters that need to be quantified as part of a robust HTPQ guideline. This shorter list of critical HTPQ variables is shown in Table II.

Table II: Critical heat treatment procedure qualification variables

All Heat Treatments
- Alloy grade/composition
- Maximum casting section size
- Time-temperature profile during heat treatment
- Furnace loading at full load condition

Additional Quench & Temper Heat Treatment Considerations
- Quenchant type
- Initial quench tank temperature
- Quench tank velocity
- Final quench tank temperature after quenching

Additional Normalizing Heat Treatment Considerations
- Air velocity during cooling

For the purposes of HTPQ development, many critical heat treatment variables can be adequately expressed by considering their effects on load thermocouple time and temperature profiles. Together, heat treatment time and temperature express the amount of energy imparted to the heat treated casting. Within limits, time and temperature during heat treatment are interchangeable, i.e., a longer heat treatment at a lower temperature can impart the same extent of heat treatment as shorter heat treatment at a higher temperature. This equivalence can be expressed using an "extent of heat treatment" term, E, that will be developed later in this treatise. While an extent of heat treatment parameter may not be able to fully predict complex heat treatment response, it is useful for comparison of heat treated castings within a narrow range of heat treatment times and temperatures.

In the following chapter key steel casting heat treatment practices will be evaluated with respect to the fundamental principles of ferrous heat treatment. The development of a robust set of HTPQ guidelines depends on careful consideration of the heat treatment fundamentals underlying successful heat treatment practices.

2.0 Evaluation of Heat Treatment Practices in Steel Foundries

2.1 Austenitizing of Carbon & Low Alloy Steels

2.1.1 Austenitizing Temperature

Carbon and low alloy steels typically undergo single or multiple austenitization heat treatments followed by rapid cooling and subsequent tempering to obtain the desired properties. During heating above the steel's upper critical temperature, ferrite and pearlite transform into austenite. During "quench & temper" heat treatments austenitizing is performed above the steel's upper critical temperature for a sufficient time to permit complete austenitization followed by quenching to obtain fully martensitic structures. Similarly, a normalizing heat treatment involves heating above the upper critical temperature for sufficient time followed by air-cooling to obtain structures that are typically ferrite/pearlite (but may contain martensite). Austenitizing temperatures commonly used for steel castings are significantly higher than the upper critical temperature indicated on the $Fe\text{-}Fe_3C$ phase diagram and are also higher than the austenitizing temperature typically used for wrought steels.

Table III summarizes handbook recommendations for austenitizing temperature ranges for wrought steels. These recommended austenitizing temperature ranges are typically 100-150F above the upper critical temperature for each alloy grade.

Table III: Recommended Austenitizing Temperatures for Wrought Carbon and Low Alloy Steels [ASM1991]

Wrought Steel Grade	Recommended Austenitizing Temperature (F)
1025	1575-1650
1030	1550-1600
1035 **1040**	1525-1575
1045 **1050** **1055** **1060** **1065** **1070**	1475-1550
1080 **1085** **1090** **1095**	1450-1500
1137	1525-1575
1138 **1140**	1500-1550
1141 **1145** **1151**	1475-1550
1536 **1541** **1552**	1500-1550
1556	1575-1625
1330	1525-1575
1335 **1340** **1345** **3140**	1500-1550
4037 **4042**	1525-1575
4047	1500-1575
4063	1475-1550
4130	1500-1600

Wrought Steel Grade	Recommended Austenitizing Temperature (F)
4135 **4140**	1550-1600
4145 **4150** **4161** **4340** **50B40** **5046**	1500-1550
50B50 **50B60**	1475-1550
5130 **5132**	1525-1575
5135 **5140** **5145**	1500-1550
5150 **5155** **5160**	1475-1550
50100 **51100** **52100**	1425-1475
6150	1550-1625
81B45	1500-1575
8630	1525-1600
8640	1525-1575
8645 **8650**	1500-1575
8655 **8660**	1475-1550
8740	1525-1575
9255 **9260**	1500-1650
94B30 **94B40**	1550-1625
9840	1525-1575

Tables IV and V compare required minimum austenitizing temperatures for 1030 and 8630 steels to the recommended austenitizing temperature for these materials in cast and wrought form and to the austenitizing temperatures typically used by steel foundries as reported in SFSA member surveys. Typical austenitizing heat treatment temperatures used for steel castings are well above the minimum required austenitizing temperature as well as being significantly above the recommended austenitizing temperatures for equivalent wrought grades.

Table IV: Comparison of required, recommended, and typically used austenitization temperatures for 1030 and 8630 type steels

	Minimum Required Austenitizing Temperature (F)	**Recommended Wrought Steel Austenitizing Temperature (F) [ASM1991]**	**Typical Cast Steel Austenitizing Temperature (F) [BRIG1970]**
1030 type steel	1495	1550-1600	1600 - 1650
8630 type steel	1495	1525-1600	1600 - 1650

Table V: Austenitizing temperature ranges reported by SFSA member foundries for carbon and low alloy steels

	Reported Temperature (F)
Respondent 1	1547 – 1816
Respondent 2	1674 – 1729
Respondent 3	1700 – 1720

2.1.2 Austenitizing Time

Long austenitizing times are also typically used in steel foundries. These hold times at the austenitizing temperature are well beyond the minimum hold times for complete transformation of the as-cast microstructure to austenite. For carbon and low alloy steels, once the austenitization temperature is reached, transformation of the microstructure to austenite happens very quickly. Figure 1 illustrates this point clearly by showing complete austenitization of the microstructures within 30 seconds at 1380F for a spheroidized plain carbon steel. However, time-honored practices, such as hold times of one hour plus one hour per inch of section size, still persist in most steel foundries.

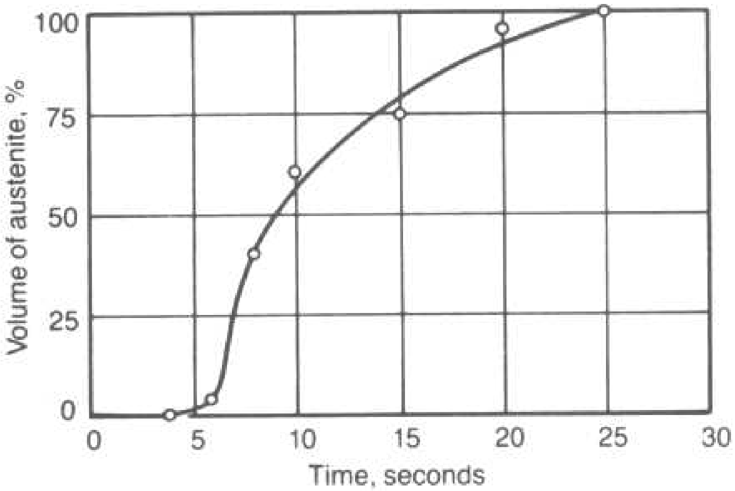


Figure 1: Volume percent austenite formed from pearlite in a eutectoid steel as a function of time at an austenitizing temperature of 1380F [KRAU1990]

Many steel foundries increase austenitizing times for heavy section castings (using hour-per-inch rules) but hold austenitizing temperatures constant. Table VI summarizes current heat treatment austenitizing time practices used by SFSA member foundries. The use of long austenitizing times persists despite the fact that the necessity of long soak times has been disputed in the literature. The 1970 SFSA Steel Casting Handbook states, "The constitutional changes sought at the maximum [austenitizing] temperature are comparatively rapid, which makes the element of time of less importance than the actual temperature itself. Generally speaking, a relatively small increase in temperature will have a far greater effect in accomplishing the desired change than a longer time at some lower temperature. This precludes the need for long soaking times." Figure 2 illustrates the influence of austenitization temperature on the rate of transformation to austenite.

Table VI: Summary of austenitizing practices used by SFSA member foundries

Specified Time at the Austenitizing Temperature	**Number of Respondents**
1 hr minimum + 1 hr/in minimum	4
Set length of time at temperature	2
1 hr/in minimum	2
Heating rate of 50C/hr, 8 hr hold	1
Less than 1 in. section size--1 hr 1 in. section size—-1.5 hr Greater than 1 in. section size—-2hr	1

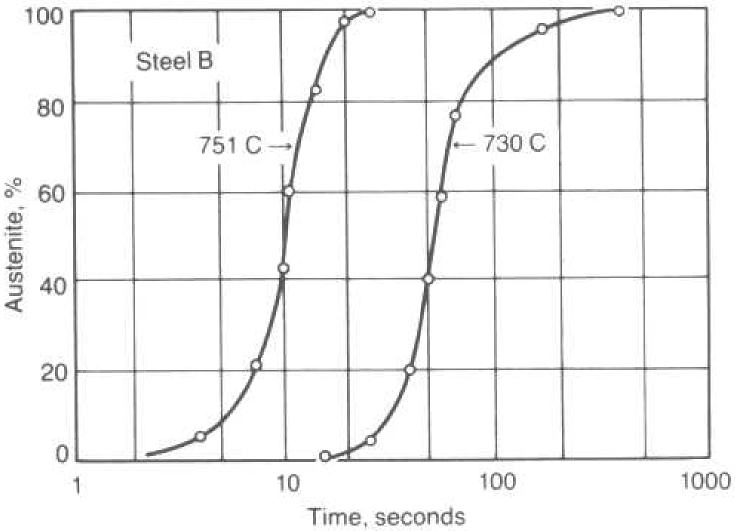


Figure 2: Effect of austenitizing temperature on the rate of austenite formation from pearlite in a eutectoid steel [KRAU1990]

The 1981 SFSA research report, *Shortened Cycle Heat Treatment of Cast Steel* [PATT1981], studied the influence of austenitizing temperature on time required for complete austenitization. It was found that when austenitizing at temperatures above 1650F, austenitizing times of much less than one hour per inch of thickness were required. The results of this study are summarized in Table VII. It should also be noted that in this study no significant austenite grain growth was observed for any of the alloys, even when austenitizing for 2.8 hours at 1900F.

Table VII: Time required for complete austenitization of cast steels at various austenitizing temperatures [PATT1981]

		Austenitizing Temperature			
		1650F	**1700F**	**1800F**	**1900F**
Alloy	**Plain Carbon**	<17min	<17min	>2min	<2min
	1.3%Mn-.25%Mo	2min	<2min	<2min	<2min
	2.4%Cr-.95%Mo	17-30min	<17min	>2min	<2min

Time Required

This study on short cycle heat treatment also showed that shorter austenitization hold times resulted in finer heat treated microstructures and slightly improved impact toughness as shown in Figure 3.

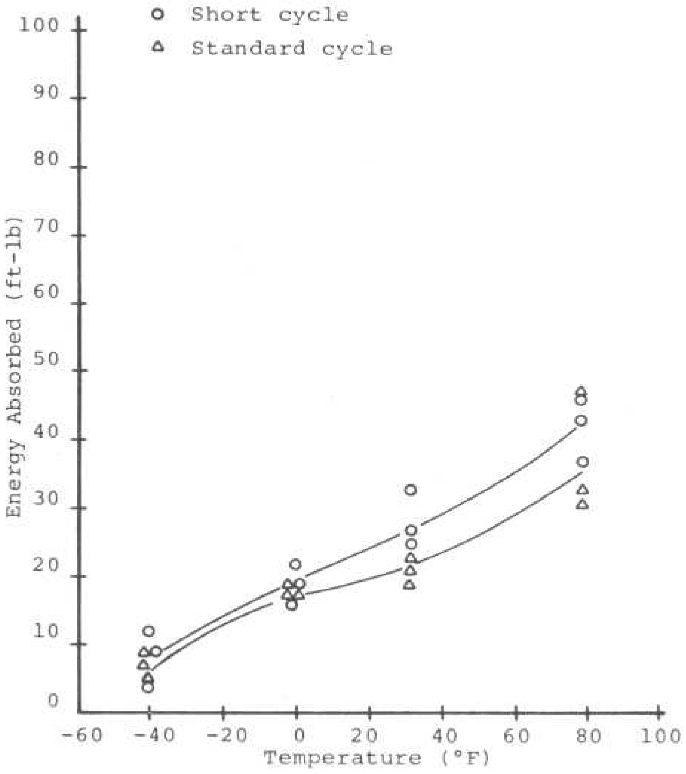


Figure 3: Comparison of Charpy V-notch impact energy as a function of temperature for standard and short cycle austenitization treatments, quenched & tempered plain carbon steel [PATT1981]

Patterson and Bates have similarly reported that the tensile and impact properties of short cycle heat-treated steels were equal or greater than those of similar castings given standard heat treatments. Hardness was not affected by short cycle heat treatment. [PATT1981]

2.1.3 Furnace Characteristics

Certainly when heat treating heavy section steel castings, sufficient time at temperature is needed to fully austenitize the centers of castings and the centers of casting loads in the furnace. Hanquist measured the time-temperature response of thick cast steel plates during austenitizing in a 'typical' foundry heat treatment furnace. Although the center of an eight-inch-thick plate did not reach temperature as quickly as the surface of the plate, the delay in reaching the required temperature was significantly less than the commonly used 'one hour-per-inch' rule would indicate. Figure 4 shows the differences in time to temperature for 3.0 in., 5.0 in., and 8.0 inch section sizes [HANQ2002]. Thermocouples were placed on the surface and at the center of each test sample. This experiment has shown that the delay in time to temperature is just minutes for the center of the section with respect to the surface. These results have been supported by heavy section heat treatment experiments performed in the laboratory as part of this study.

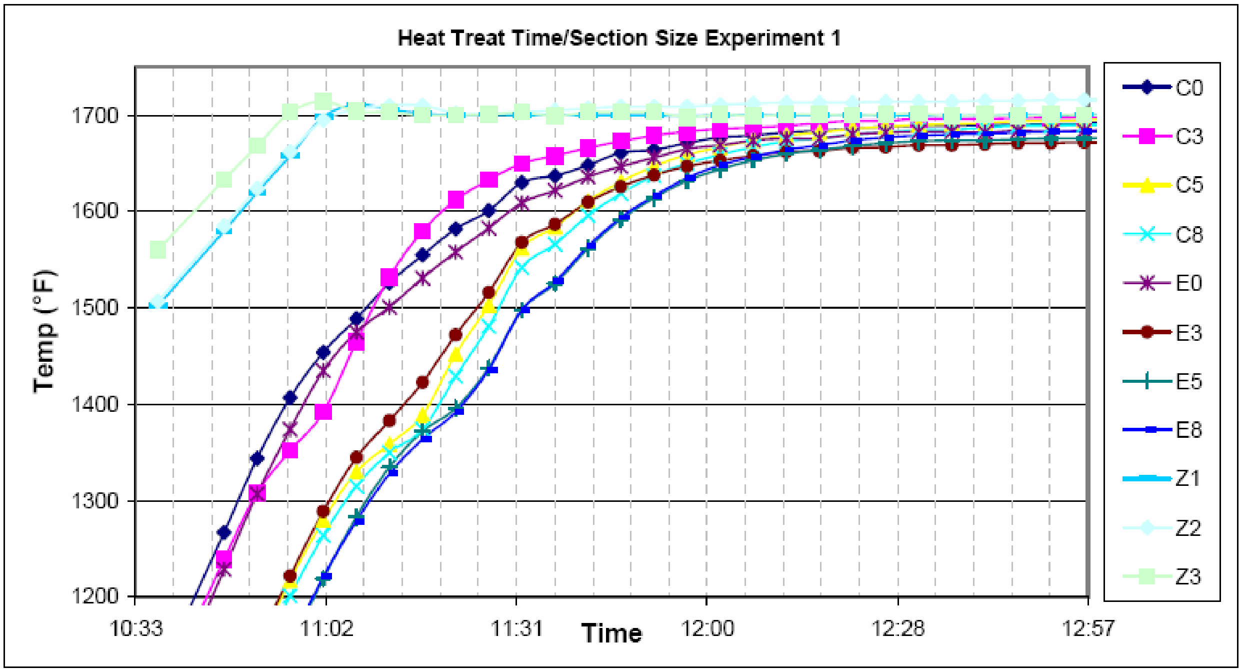


Figure 4: Time-Temperature profiles for 3.0, 5.0, and 8.0 inch section sizes during an austenitizing test. Thermocouples were placed on the surface and at the center of each test block. [HANQ2002]

Because the transformation of room temperature microstructures to austenite happens relatively quickly, it is possible to end the austenitizing portion of the heat treatment cycle shortly after the castings have reached an appropriate temperature at the center of the thickest section. Patterson and Bates studied 5 inch thick sections placed into a furnace at 1650-1700F and found that the temperature of the center of the castings lagged behind that of the surface by only about 15 minutes. The SFSA research report, *The Effect of Heat Treatment Variables on* *the Toughness of Cast Steels,* by Briggs [BRIG1958] showed a similar result. Briggs placed cast steel plates of various section sizes into furnaces at various temperatures. The time-temperature profiles of the surfaces and the centers of the castings from his work are shown in Figures 5-7.

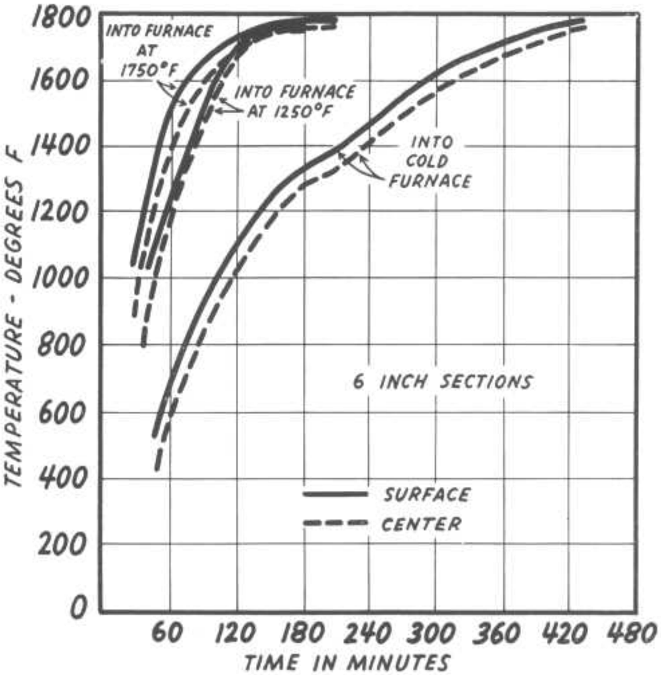


Figure 5: Heating rates of 6.0 inch sections of CrMo and MnNiCrMo cast steels in a 1750F production furnace [BRIG1958]

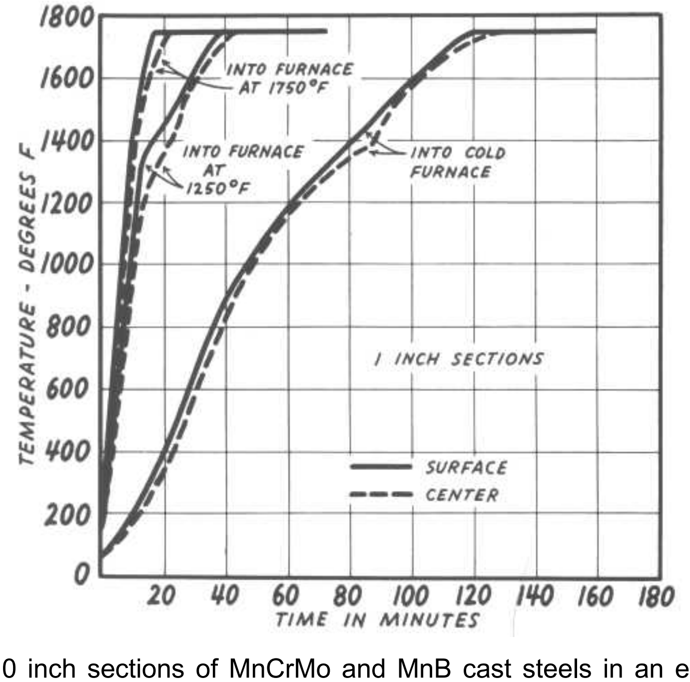


Figure 6: Heating of 1.0 inch sections of MnCrMo and MnB cast steels in an experimental furnace at 1750F [BRIG1958]

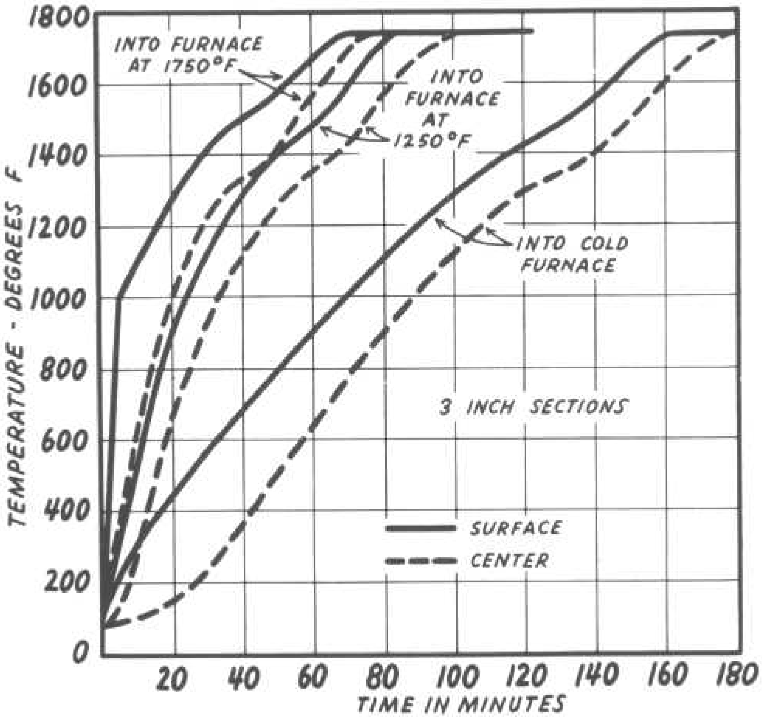


Figure 7: Heating of 3.0 inch sections of MnCrMo and MnB cast steels in an experimental furnace at 1750F [BRIG1958]

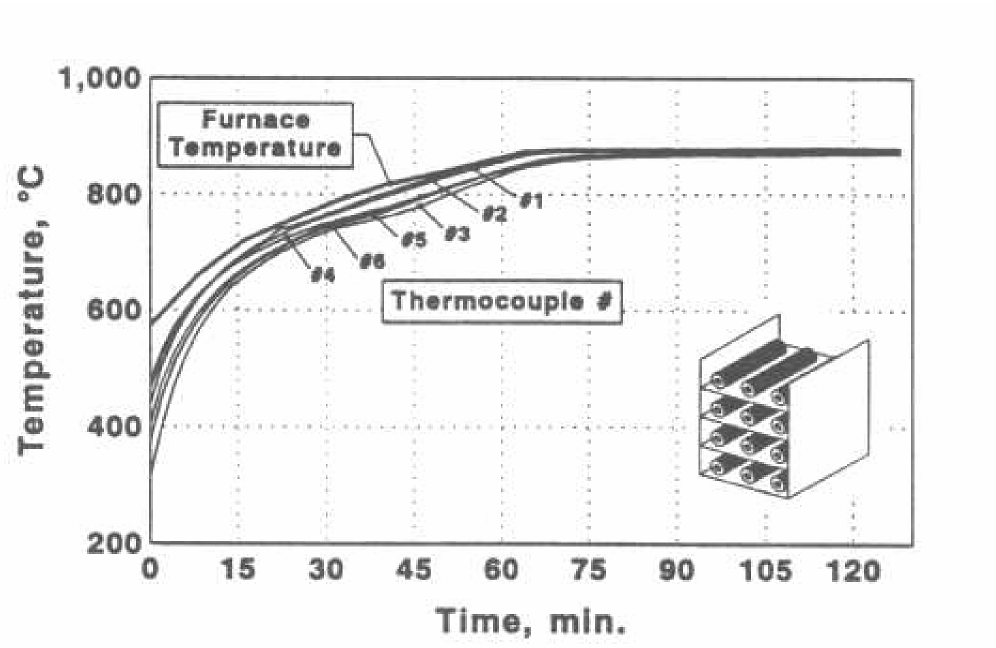
Practical use of shorter austenitizing times requires knowledge of furnace heating dynamics. This includes not only knowledge of the section sizes being heat treated but also furnace heat-up loading effects.

The furnace itself and its thermal characteristics must also be considered as a factor in HTPQ testing. Heat treatment furnaces are typically sold or purchased with the following characteristics in mind: loading capacity (mass), thermal capacity (BTU/hr, maximum attainable temperature), temperature homogeneity or uniformity (unloaded), chamber dimensions, and motor/blower rate. Therefore, for HTPQ it may be necessary to do qualifying tests on every furnace used if furnace load instrumentation is not used during HTPQ testing.

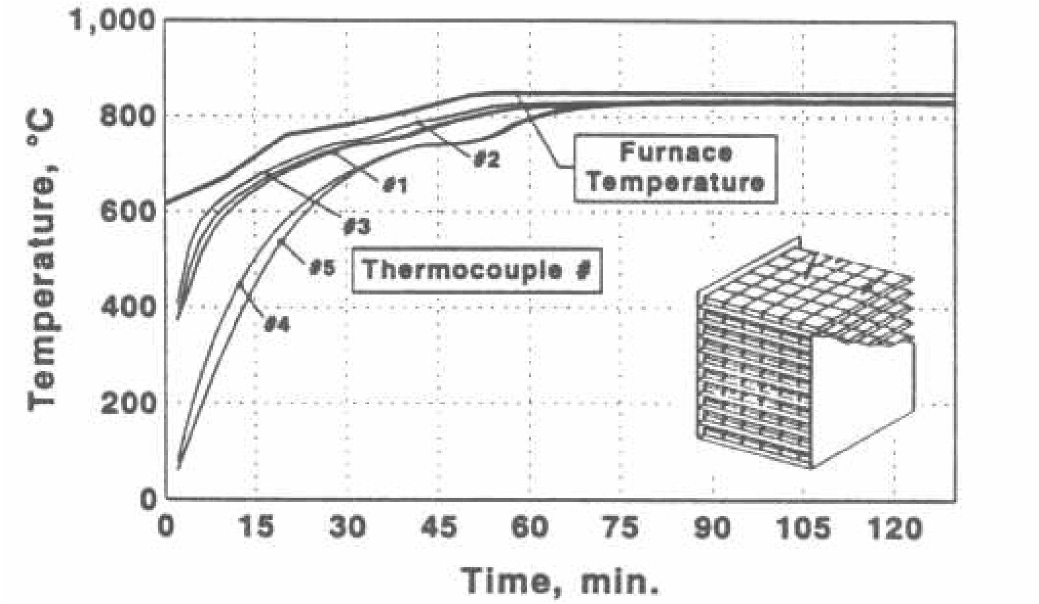
2.1.4 Furnace Loading

Furnace loading is a key heat treatment parameter influencing the time-temperature profiles of furnace loads during heat-up to the austenitizing temperature. Loading must consider the weight of the furnace load, as well as the load density. Furnace loading varies considerably among foundries and also varies significantly from heat treatment to heat treatment at a given foundry. Many foundries carefully plan their furnace loading to provide ‘adequate circulation’ of furnace gases through the load for consistent austenitization. However, furnace loading practices in steel foundries are very furnace and casting load dependent. Baskets full of small castings might give the same overall furnace load density as a whole furnace filled with fewer larger castings, but the castings at the center of the basket will be somewhat insulated and will take longer to reach the proper temperature. Thus local load density as well as overall furnace load density must be considered.

Figure 8 shows time-temperature profiles for different locations in the furnace load for two different types of furnace loading of wrought steel parts by a commercial heat treater. In this example the loading strategy that provides for more space between parts results in better air circulation and results in better thermal uniformity throughout the load. A tightly-packed heat treatment load can substantially increase the amount of time needed to attain steady-state casting load temperature.



a) Heat treatment of disks



b) Heat treatment of chipper blades

Figure 8: Temperature response of loaded heat treatment furnaces during austenitizing [ARON1994]

The influence of the total mass of the furnace load on temperature response can be seen in Figures 9 and 10. Although these figures and subsequent figures show furnace loading effects in "convection" tempering furnaces, similar furnace loading effects can be expected in traditional furnaces used for austenitizing or tempering. Increasing the size of the load increases the amount of time for the furnace to reach steady-state temperature, whether or not the load is added when the furnace is at room temperature or is preheated. The load in Figure 10, (fewer specimens), has a greater overall mass than the load studied in Figure 9. The corresponding increase in time to reach steady-state temperature for the same furnace is evident.

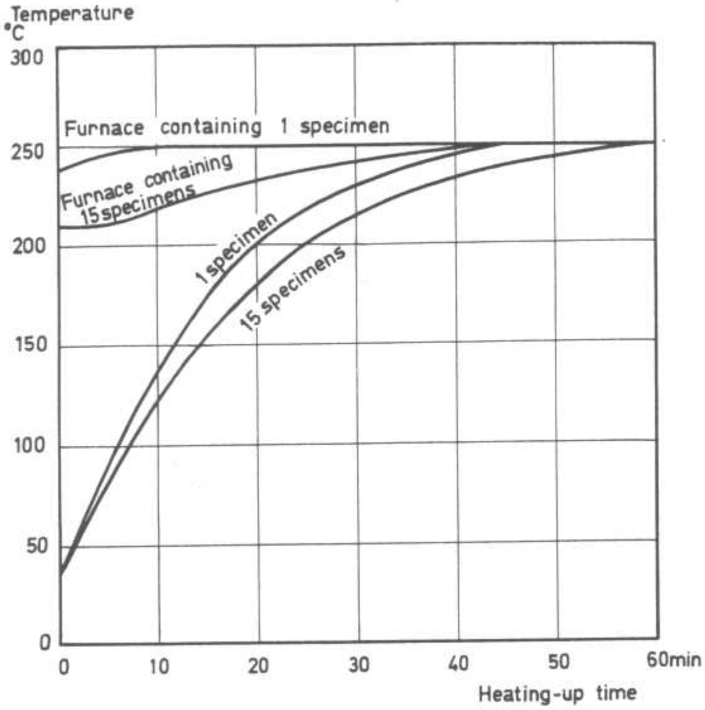


Figure 9: Time for heating to 250C in a convection furnace. Specimen size 50mm diameter x 100mm, 1 and 15 specimens respectively [THEL1975]

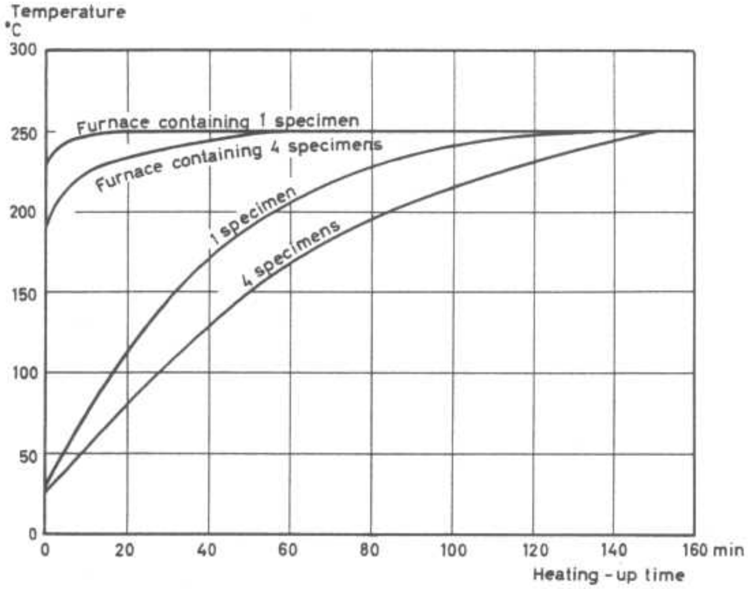


Figure 10: Time for heating to 250C in a convection furnace. Specimen size 150mm diameter x 300mm. 1 specimen and 4 specimens respectively [THEL1975]

The decrease in time needed to achieve steady-state temperature when the load is placed into a hot furnace can be seen in Figure 11. The additional effective "furnace loading" to get the walls of a cold heat treatment furnace up to temperature is significant.

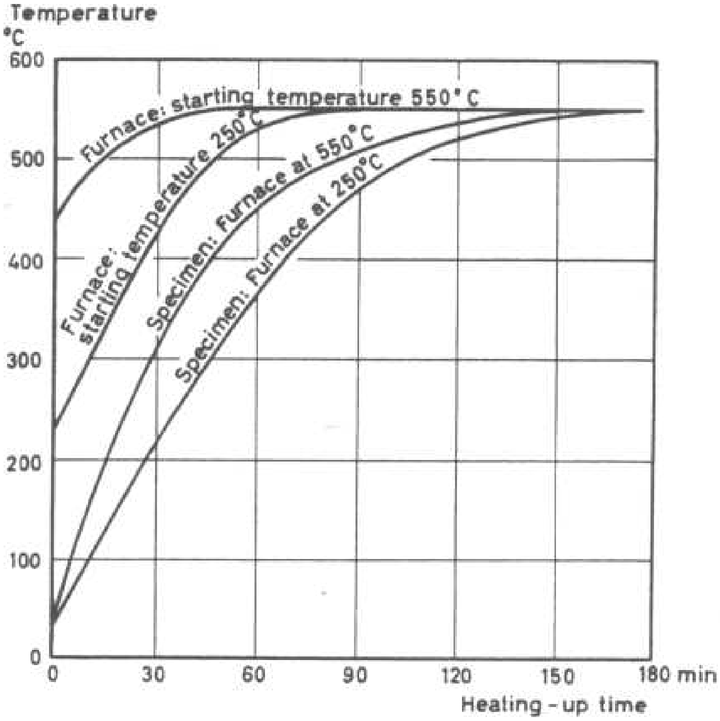


Figure 11: Dependence of overall heating time on initial furnace temperature for a convection furnace. Specimen size 150mm diameter x 300mm. 2 specimens [THEL1975]

During actual heat treatment both casting section size as well as overall and local furnace loading will affect the time required to reach the austenitizing temperatures. Figure 12 shows the time difference to reach the set-point temperature for both a large load, and a large section size. This figure also illustrates the importance of using load thermocouples rather than simply measuring time in the furnace when conducting heavy section heat treatments in loaded furnaces.

These heat treatment data clearly show that the long heat treatment hold cycles commonly used by steel foundries can be traced to the delays in getting the center of furnace loads up to the desired austenitizing temperature in heavily loaded furnaces. In particular it might be expected that control strategies based on the temperature of the surface of the casting load rather than on the furnace temperature itself could be expected to shorten the time necessary to fully austenitize castings.

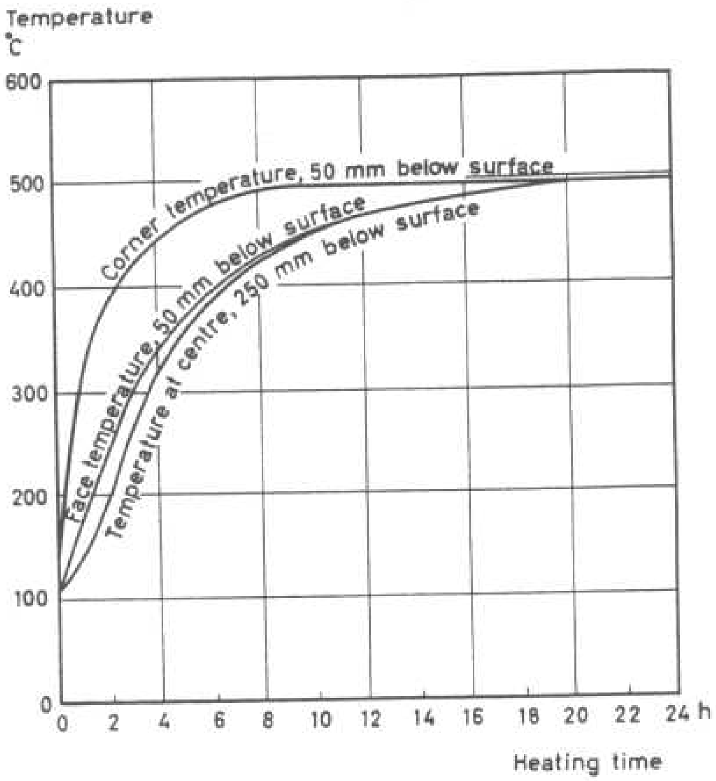


Figure 12: Heat-up time in an electric muffle furnace for a die block measuring 2300 x 950 x 500mm (Dimensions of furnace: 6500 x 1400 x 1100mm) [THEL1975]

Laboratory heat treatment trials were also performed at Penn State University to investigate shorter cycle heat treatment strategies for heavily loaded furnaces with large casting section sizes. Table VIII shows the results of several of these trials when furnace loads were placed in pre-heated furnaces. It was found that there is no significant reduction in the time to reach the temperature if the furnace was controlled using the surface- or center-mounted load thermocouples instead of the furnace controller thermocouple (controller set-point held constant). Artificially raising the controller set-point and placing the load into a hotter furnace decreased the time required to reach austenitization temperature only slightly.

Table VIII: Summary of PSU short cycle heat treatment studies in a heavily loaded laboratory furnace

Set-point	Control Thermocouple Location	Time for Casting Center to reach 855F (min)	Time for Casting Center to Reach 895F (min)	Maximum Temperature and Time Overshoot at Casting Surface	Maximum Temperature and Time Overshoot at Casting Center
900F	Furnace	82	>100	None	None
900F	Surface of Casting	86	91	917F, over set-point for 60min	927F, over set-point for >80min
900F	Center of Casting	85	91	950F, over set-point for 28 min	927F, over set-point for 15min
1200F reduced to 900F when center reaches 900F	Center of Casting	69	75	953F, over set-point for 24min	922F, over set-point for 18min
1200F reduced to 900F when surface reaches 900F	Surface of Casting	70	76	904F, over set-point for 4 min	919F, over set-point for >30min

High austenitizing temperatures and long austenitizing times commonly used by steel foundries are overly conservative and are driven by the need to get the center of casting loads in large heat treatment furnaces up to the desired austenitizing temperature. The centers of heavy section size castings require only slightly more heat treatment time than the surfaces of the castings to reach desired temperatures. Consequently, it is the furnace heat-up and the high furnace loading when heat treating heavy section-size castings rather than the section size itself that increases the required austenitizing times. The use of thermocouples, placed in the center of casting loads can be an effective way to develop effective austenitizing cycles that do not require excessive austenitizing times or temperatures.

2.1.5 Extent of Austenitization

Carbon diffusion based calculations can provide insight into the adequacy of heat treatment procedures and practices used by steel foundries. This diffusion distance can be estimated using Fick's second law as described in detail in Appendix A. "Extent of heat treatment" estimates based on localized time and temperature response (obtained through load thermocouples) can be used to compare the variations in heat treatment response within foundry heat treatment furnaces. The extent of austenitization may be calculated using Equation 1 below:

$$E = \frac{.3\sqrt{D_o t_{ramp,load} e^{\frac{-Q}{RT_1}}} + \sqrt{D_o t_{hold,load} e^{\frac{-Q}{RT_1}}}}{.3\sqrt{D_o t_{ramp,controller} e^{\frac{-Q}{RT_1}}} + \sqrt{D_o t_{hold,controller} e^{\frac{-Q}{RT_2}}}} \qquad (1)$$

Where:

T_1 = 95% of difference between steady state temperature room temperature
T_2 = set-point temperature
$t_{ramp,load}$ = time in seconds for load to reach T_1
$t_{hold,load}$ = time in seconds for load at or above T_1
$t_{ramp,controller}$ = time in seconds for controller to reach T_1
$t_{hold,controller}$ = time in seconds for controller at or above set-point
D_0 is the diffusion coefficient
Q is the activation energy and
T is the temperature in degrees Kelvin

Extent of heat treatment estimates express the amount of carbon diffusion achieved for a given casting or casting load relative to what would have been achieved had the casting load been exactly at the temperature of the furnace thermocouple for the duration of the heat treatment. This extent of heat treatment parameter is much more strongly influenced by differences in temperature than by changes in time. Although the extent of austenitizing heat treatment parameter is useful for expressing austenitizing variations in a furnace, it cannot be directly used to predict as-quenched hardness. A complete description of these “extent of heat treatment” calculations based on localized time and temperature responses during austenitizing/solutionizing or tempering are described in Appendix A.

2.2 Solutionizing of High Alloy Steels

Heat treatment practice issues during solutionizing of high alloy steels are similar to the heat treatment issues for the austenitizing of carbon and low alloy steels. Solutionizing and austenitizing are very similar in terms of the critical heat treatment practices that are necessary for heat treatment success. However, high temperature heat treatment of high alloy steels (solutionizing) differs from the high temperature heat treatment of carbon and low alloy steels (austenitizing) in terms of the metallurgical reactions that take place. Temperatures typically used during the solutionizing of high alloy steels are also somewhat higher than the temperatures used to austenitize carbon and low alloy steels. As stated by Haro [HARO1999]:

> “Depending on the alloy, temperatures in the 1040C to 1205C (1900F to 2200F) range assure the complete solution of all carbides and sigma phase, which sometimes form in highly alloyed stainless steels. Solution annealing (solutionizing) requires that the steel remains for enough time to dissolve the carbides and a rapid cooling to prevent new precipitation of the secondary carbides in the 540C to 870C (1000F to 1600F) temperature range.”

The heat treatment literature is noticeably silent on critical issues governing the solutionizing of high alloy steel castings. At the solutionizing temperatures commonly used by steel foundries, re-solution of carbidic phases can be expected to take place very quickly. This is reflected in the specification language used for the cast corrosion resistant stainless steels that states, "All castings should be held at temperature for a sufficient time to reach uniform heating" [ASTM1999]. This strongly suggests that (as for carbon and low alloy steels) the critical heat treatment practice issue is to get the furnace load to the desired temperature. Excess furnace hold times are not necessary, except to guarantee that all portions of the furnace load reach the desired temperature. As for the low alloy steels, the high solutionizing temperatures and the long solutionizing hold cycles commonly used by steel foundries for high alloy steel grades can be traced to the delays in getting the center of furnace loads up to the desired solutionizing temperature. Because of the very high solutionizing temperatures used for many of the high alloy steels, excessively long heat treatment cycles and excessively long solutionizing times are very costly and should be avoided.

2.3 Quenching of Carbon and Low Alloy Steels

Classic quench & temper heat treatments require that steels are fully austenitized and are subsequently quenched at a rapid enough rate to obtain fully martensitic structures. The critical cooling rate to avoid the "pearlite nose" of the austenite transformation diagram depends on the hardenability of the alloy being quenched. The hardenability of an alloy is based on its chemical composition and can be readily calculated. Less hardenable alloys require more rapid cooling to obtain martensite. Casting section size is an important consideration in quenching. As the casting section size increases, the alloy content of the steel and/or the quench severity must be increased to insure adequate quenching cooling rates at the center of the casting. Also, the transfer time from the austenitizing furnace into the quench tank must be short enough to prevent premature pearlite formation prior to immersion in the quench tank. It should be noted that some steel castings are "quenched" in the physical sense, but the cooling rates used are not sufficient to achieve martensite transformation. This rapid cooling can improve casting mechanical properties significantly, even if the end microstructure upon quenching is not fully martensitic.

2.3.1 Quenchant Characteristics

A basic understanding of the fundamental behavior of quenchants is necessary to understand the complex phenomena taking place when a load of steel castings is placed into a quench tank. When austenitized steel is quenched in water, three stages of cooling occur. The first stage is characterized by the formation of a vapor blanket around the hot metal. This vapor blanket provides only a slight cooling effect. Because it insulates the metal from the liquid quenchant, cooling rates are not very high. The second stage is the nucleate boiling stage. At this point, violent boiling begins at the metal-quenchant interface. The temperature at which this stage begins is dependent on the quenchant and is typically independent of the initial temperature of the metal. The third cooling stage is the convective cooling stage, which begins when the metal cools below the boiling point of the quenchant. The rate of heat removal in this stage is slower than during the nucleate boiling stage. Heat transfer rates during quenching are strongly influenced by variables such as quenchant temperature, viscosity and agitation. [TOTT1993] Figure 13 illustrates the changes in cooling rate with quenchant temperature. In the higher temperature regions, representing the vapor blanket stage, the cooling rates are not as great as in the intermediate violent boiling stage. As the quenchant cools further, the cooling rate again drops as the convective cooling stage is entered.

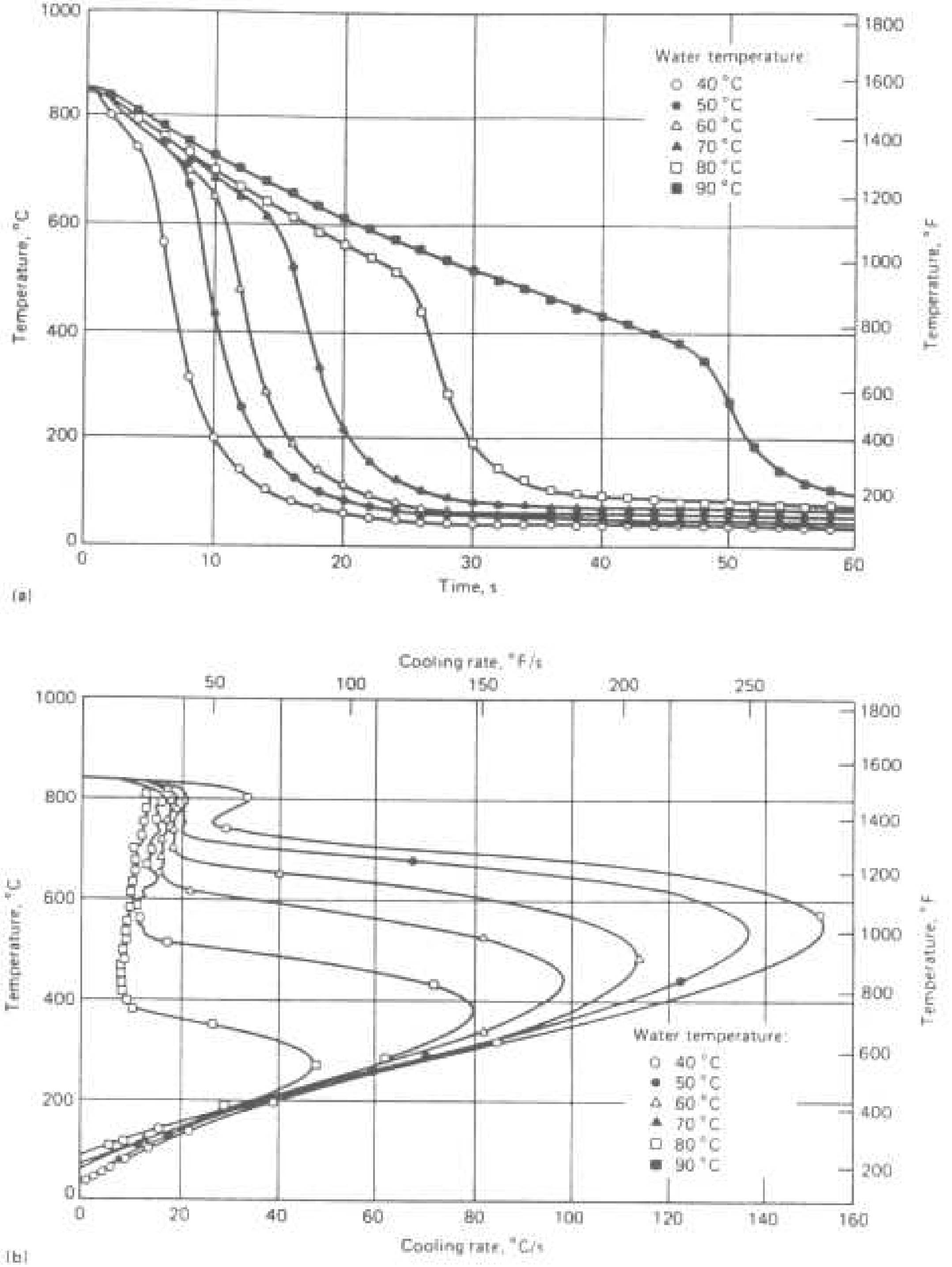


Figure 13: Effect of quench bath temperature on heat removal using a Wolfson probe. (water quenchant; velocity of 50ft/min) [TOTT1993]

Most steel foundries use temperature-controlled, agitated water quench tanks to ensure adequate quenching of casting loads. Agitation helps to interrupt the vapor blanket that forms in the first stages of cooling. Large, complex casting shapes and large quench tank loads can stretch the limit of quench tanks to provide adequate quench severity during quenching. Careful control of water quench tank temperature and agitation is necessary to control quench severity. According to the *Handbook of Quenchants and Quenchant Technology* [TOTT1993]:

> "Quench severity, as measured by cooling curve analysis, is dependent on linear flow rate, turbulence, quenchant temperature, both interfacial and bulk solution viscosity, uniform surface wetting, and direction of fluid flow impinging on the hot metal surface. Nonuniformity of any of these variables throughout the quench zone and across the boiling surface will result in nonuniform heat removal from the surface of the part during the quench, creating excessive thermal gradients that may cause distortion and nonuniform hardness."

Tables IX and X show the effects of quenchant temperature and velocity on the effectiveness of water quenchants for removing heat during the quenching of steel. The quench severity values (Grossman Numbers) shown in these tables were measured experimentally by quenching small test specimens into relatively large quench tanks. It is clear from this data that lower water temperatures and increased quenchant velocities will provide a greater quench severity.

Table IX: Expected Grossman numbers and film coefficients for water during quenching [TOTT1993]

Water Temperature	**Quenchant Velocity (ft/min)**	**Grossman Number (H)**	**Effective Film Coefficient Btu/ft^2·h·°F**
90F	0 ft/min	1.1	880
90F	50 ft/min	2.1	1600
90F	100 ft/min	2.7	2100
90F	150 ft/min	2.8	2100
130F	0 ft/min	0.2	180
130F	50 ft/min	0.6	440
130F	100 ft/min	1.5	1100
130F	150 ft/min	2.4	1850

Table X: The effect of water temperature on cooling rates and film coefficients in 1.5in diameter 4130 steel bars water quenched from 1550F [TOTT1993]

Water Bath Temp	**Velocity ft/min**	**Cooling rate at 650F**	**Film Coefficient Btu/ft^2·h·°F**
80F	50 ft/min	26.2	1652.5
90F	50 ft/min	26.3	1589.4
100F	50 ft/min	25.8	1346.5
120F	50 ft/min	25.9	617.1
140F	50 ft/min	25.7	132.8
160F	50 ft/min	24.6	73.5
180F	50 ft/min	24.2	60.1
200F	50 ft/min	23.7	42.5
212F	50 ft/min	22.6	35.8

The poor quenching performance of water at elevated temperatures is clearly shown in Figures 14 in terms of cooling rate and in Figure 15 in terms of the resultant quenched hardness of steel bars. Figure 14 presents various snapshots of cooling curve analysis and illustrates the dramatic drop-off of water's quenching effectiveness as the quenching temperature increases. Figure 15 shows the quenched hardness and the depth of hardness for Jominy end quench test bars that have been end-quenched at different water temperatures. The quenched hardness varied tremendously and dropped dramatically as water temperature increased beyond 110F. Maintaining quench tank temperatures below 110F and providing adequate, consistent agitation insures consistent heat treatment quenching from load to load as quench tank temperature changes throughout the day. Similarly, low quench tank temperatures and adequate water velocities can be expected to provide less variation in effective quench severity from the edge to the center of heat treatment loads.

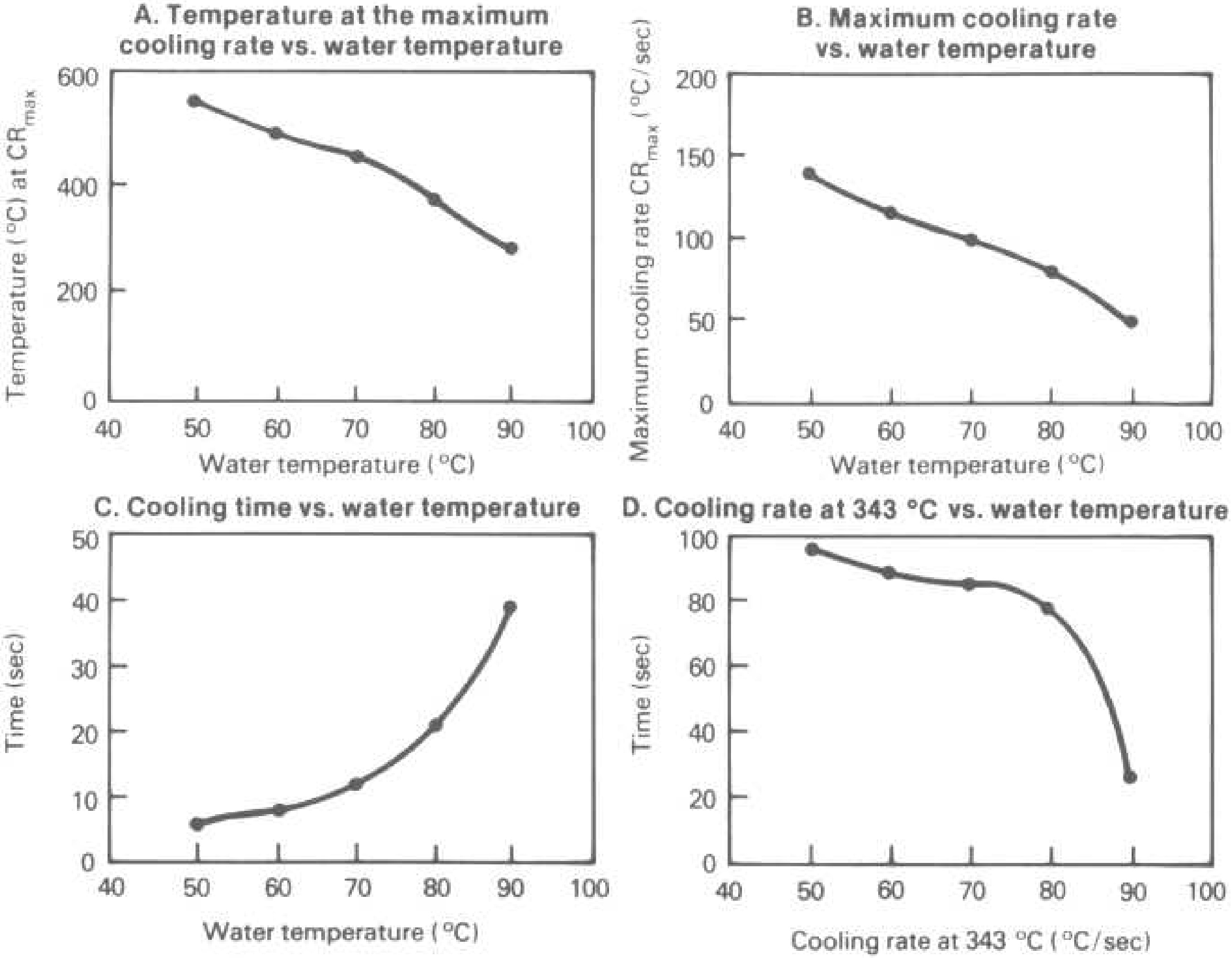


Figure 14: Analysis of cooling curve data during quench severity studies of water quenchants [TOTT1993]

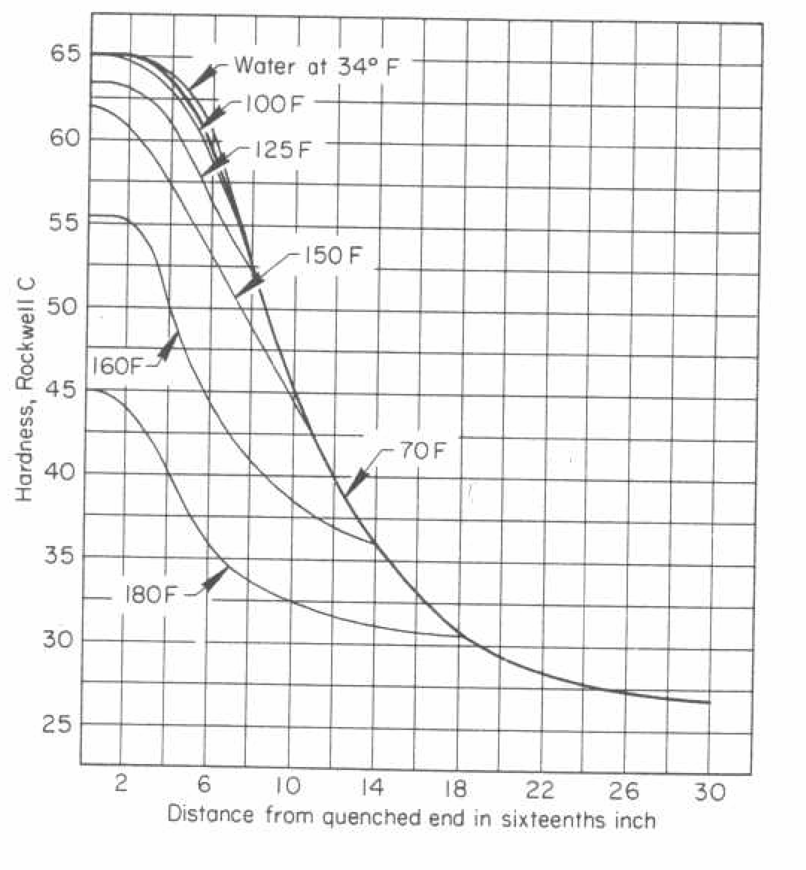


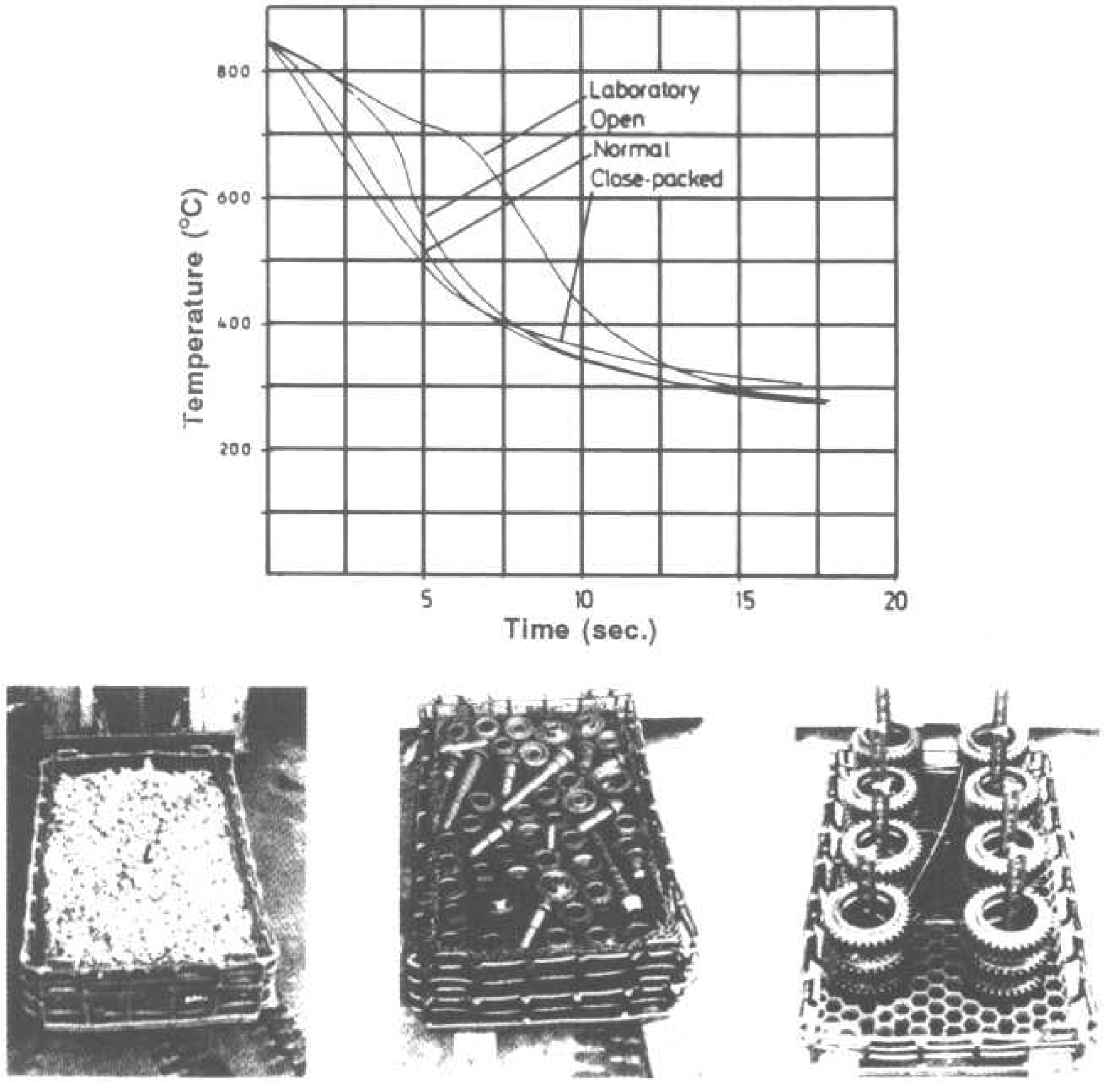
Figure 15: The effect of end-quench water temperature on the resultant hardness of Jominy end-quench bars [BOYE1988]

2.3.2 Quench Tank Loading Effects

Quenching studies have shown that agitation of the quenchant increases quench severity. However, if casting loads are packed together too closely during quenching, the castings will be shielded from the flowing coolant, and a uniform quench will be impossible to achieve. According to the *Handbook of Quenchants and Quenchant Technology* [TOTT1993]:

> Optimization of fluid flow around the part during quenching is necessary for uniform hardness and minimal quench distortion, cracking, and stresses. Therefore, proper part racking for quenching is especially important.

The effective severity of a quench can be expected to vary significantly from the outside of a quench tank load to the center of a densely-packed quench tank load, independent of casting section size. Even when the combination of casting section size, hardenability and overall quench tank quench severity are sufficient to ensure adequate quenching of a given casting section, adequate quenching of casting sections in the center of quench tank loads is not guaranteed. Figure 16 shows the variation in cooling curve performance with packing density. It is clear that open packing strategies during quenching provide increased cooling performance.



a. "close-packed" b. "normal" c. "open"

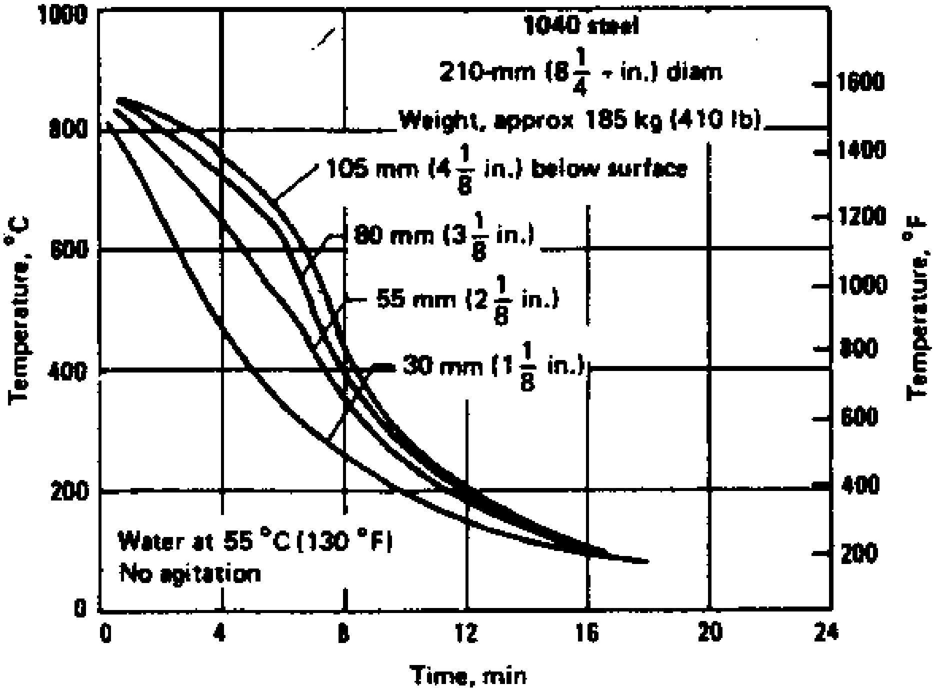
Figure 16: Variation of quenching cooling curve performance at the center of casting loads at various packing densities for a water quenchant [TOTT1993]

General recommendations on appropriate part packing for quenching can be found in the literature [TOTT1993]:

> Long, slender parts should be suspended. Symmetrical parts, such as bearing races and cylinders, can be stacked and supported on a rack or grid. Flat parts, such as saw blades, clutch plates, and so on, are best supported on horizontal slotted rods that provide the necessary separation for fluid contact. Coils of wire should be supported either vertically on a spider-type grid or horizontally on support rods. Small parts can be loaded into a perforated ladle or basket to facilitate quenchant contact upon immersion. Fixture design should be simple, free of welds (if possible), and easy to maintain. The combined weight of parts and fixtures must be limited to allow for sufficient heat transfer during the quench to minimize temperature rise.

These guidelines, though useful, are difficult to apply for steel castings with complex geometry and that often have variations in section size. Clearly, careful control of casting loads to ensure consistent quench tank loading is extremely difficult for steel foundries.

The overall mass of the parts to be quenched compared to the size of the quench tank strongly influences the ability of a quench tank to adequately extract heat. Figure 17 illustrates the effect of mass as well as section size on cooling rates during water quenching.



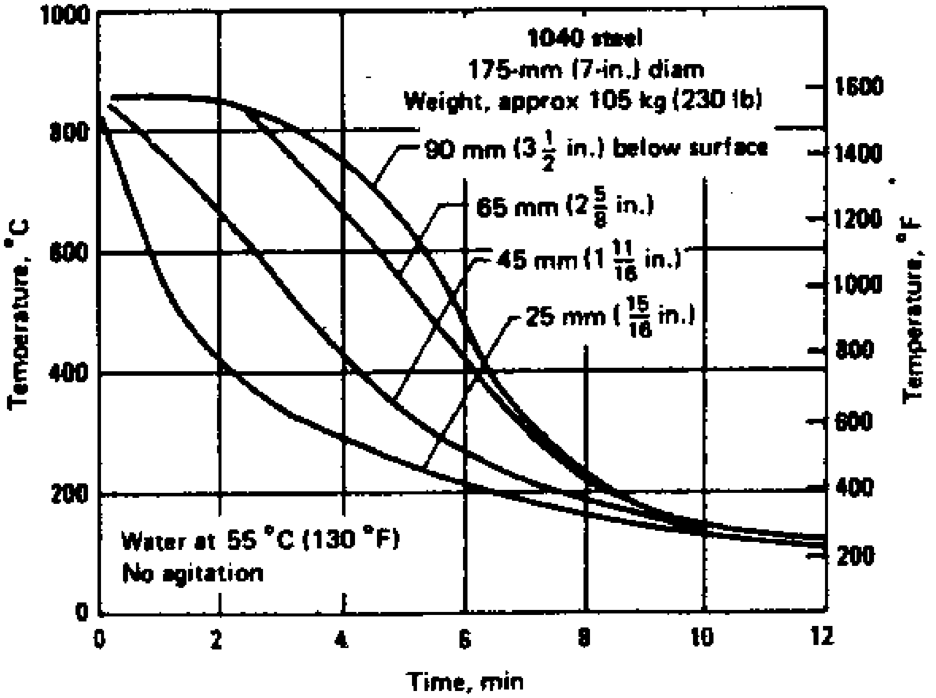


Figure 17: The effect of steel mass and section size on the cooling rates of steel sections quenched in hot water without agitation [BOYE1988]

2.3.3 Quench Delay

The literature is noticeably silent on the influence of heat treatment conditions and practices on temperature drops of casting loads during quench delays. This is compounded by the fact that surface temperatures of oxidized casting surfaces may be lower than the actual casting surface temperature. Temperature drops due to quench delays can be similar to the cooling rates observed when normalizing castings.

Normalizing is the process of heating steel fully into the austenitizing range, holding to fully convert the structure to austenite, and then cooling in air at room temperature under natural or forced convection. Normalizing cooling rates are not fast enough to avoid the pearlite nose; therefore the resultant grain structure is a mixture of fine pearlite with ferrite or cementite. Quenching cooling rates for water quenches of heavy section castings may range from 1-9F/s, whereas cooling rates for the same section size during normalizing will be far lower: 0.1-0.6F/s; see Figure 18

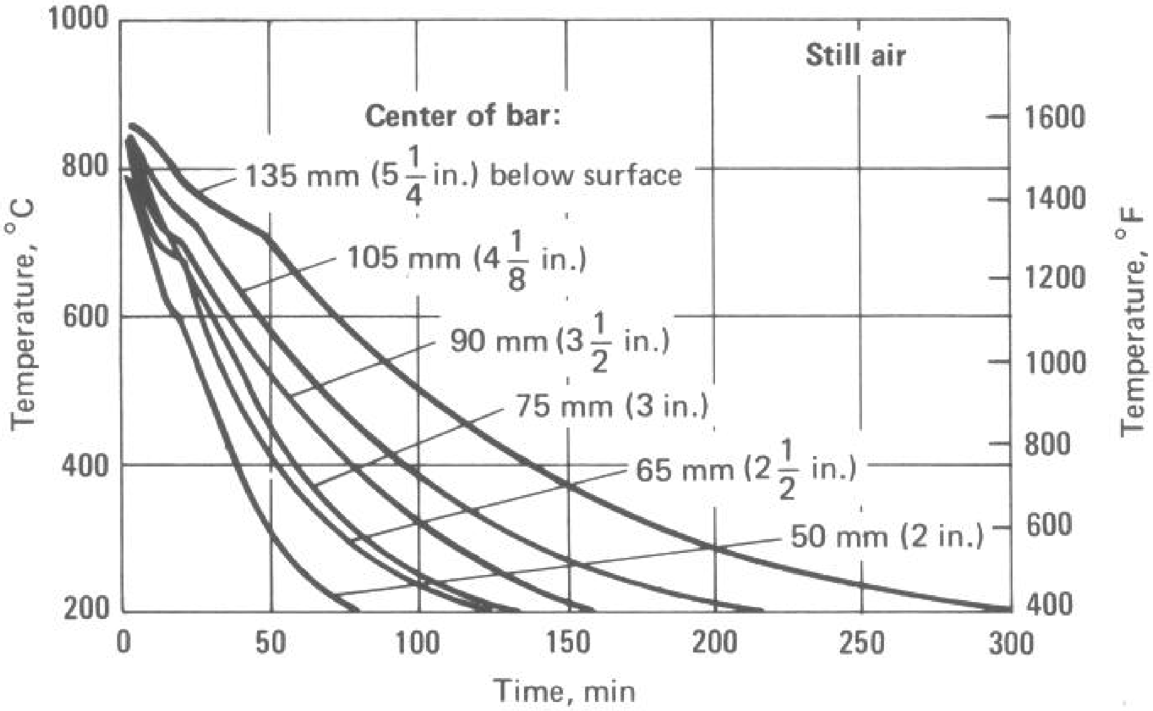


Figure 18: Still air quenching at the center of plain carbon steel bars [ASM1990]

2.3.4 Normalizing of Carbon & Low Alloy Steels

Furnace time and temperature considerations during austenitizing for normalizing heat treatments are very similar to time and temperature considerations for quench & temper heat treatments. However, incomplete austenitization during normalizing heat treatments will not have as dramatic an effect on final normalized (or normalized & tempered) properties as will occur for quenched & tempered properties. Similarly, variations in cooling rates during normalizing will have a less significant effect on final properties after heat treatment.

The heat treatment literature is silent on the influence of normalizing heat treatment variables (austenitizing and cooling rate) on the resultant mechanical properties from normalizing or normalize & temper heat treatments. This suggests that heat treatment process control requirements for these heat treatments are much less demanding than for quench & temper heat treatment.

The effects of heat treatment practice parameters on cooling rates during normalizing can also give insight into the acceptable quench delay times for quench & temper heat treatments. Figure 18 shows the influence of section size on the cooling rates that can be expected during normalizing or during casting transfer from the austenitizing furnace to the quench tank. This cooling from 1450F to 1100F in 25 minutes for a 4.0 inch section indicates that a quench delay time of a half hour reduces the temperature of the casting as much as two minutes in a water quench tank [ASM1990].

2.3.5 Quenching/cooling of High Alloy Steels

Rapid cooling of high alloy steels after solutionizing is also an important heat treatment step. Quenching prevents the re-precipitation of undesirable carbide phases that lower corrosion performance. Although the metallurgical reactions taking place during quenching of high alloy steels are different than the metallurgical reactions taking place during austenitizing of low alloy steels, the quenching practice issues are also similar for both high alloy and low alloy steels. However, the technical literature does not provide clear quantitative guidance on critical quenching parameters for high alloy steels. Figure 19 illustrates the TTT behavior of a wrought duplex stainless steel. The precipitation kinetics for most high alloy steels (austenitics, ferritics, martensitic or duplex grades) are not well known, making it difficult to quantitatively determine quenching requirements for high alloy grades of cast steels.

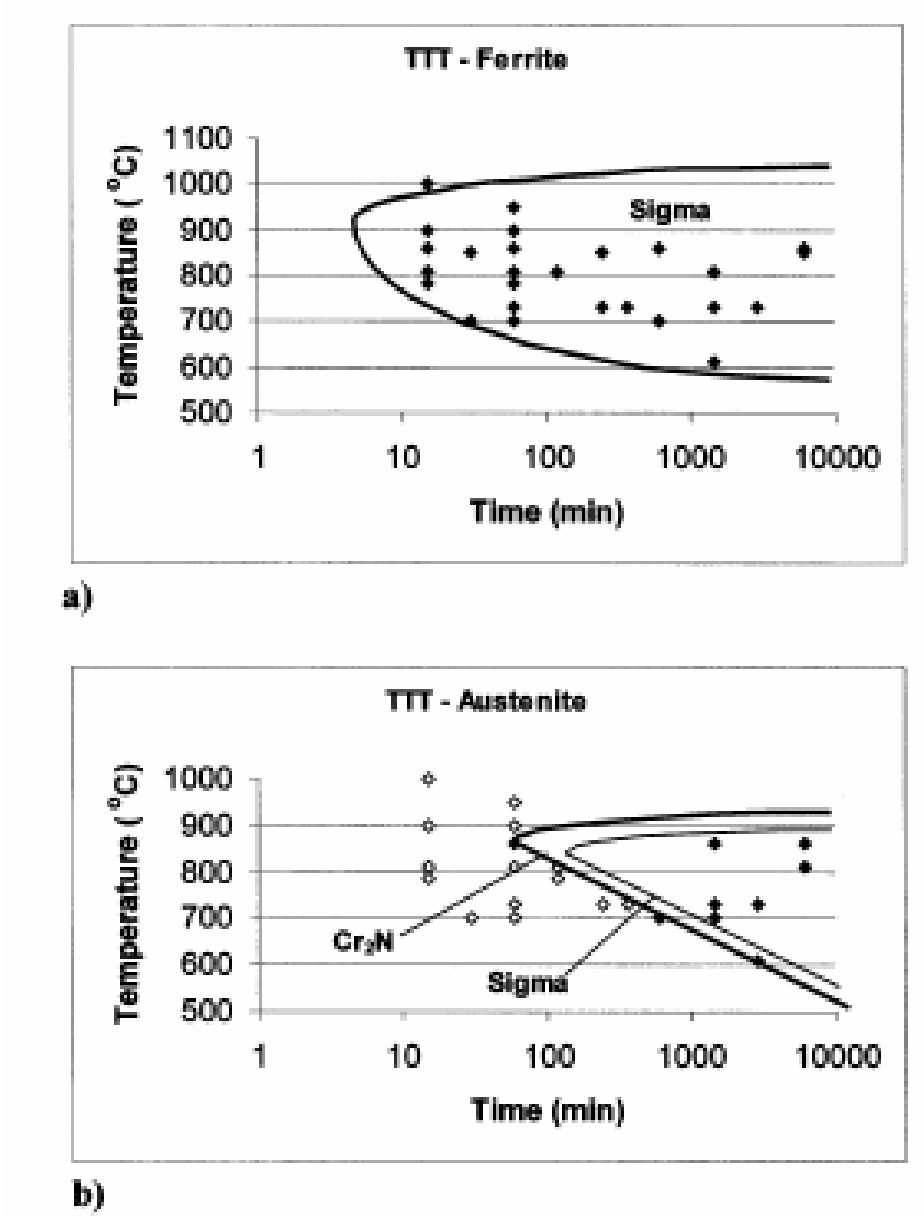


Figure 19: TTT diagrams of 25%Cr-16%Mn-.54% ferritic-austenitic stainless steel in ferrite (a) and austenite (b) [MACH2000]

The lack of critical technical information regarding precipitation kinetics during cooling from solutionizing temperatures suggests that rapid water quenching of high alloy steels is not as critical for the common high alloy grades as it is for carbon and low alloy steels. Even slower quenching cooling rates from water quench tanks operated at higher water temperatures and lower quenchant velocities may be sufficient for reasonable section sizes of the widely used high alloy steels.

It must also be pointed out that the heat treatment “success” for high alloy steels must be typically assessed in terms of adequate corrosion performance instead of simply adequate mechanical properties. Carbides remaining in solution or re-precipitated during slow cooling from inadequate heat treatment do not typically degrade the mechanical properties but can significantly degrade the corrosion performance.

2.3.6 Pre-qualification of High Alloy Steels Using HTPQ Ratings

The successful solutionizing of a high alloy steel casting depends on sufficient time at temperature during solutionizing to resolutionize all of the carbide particles present in the as-cast microstructure followed by rapid enough cooling from the solutionizing temperature to prevent the re-precipitation of these carbides during cooling to room temperature. Unfortunately, the literature is noticeably silent on the solutionizing and re-precipitation kinetics of either wrought or cast high alloy steels.

For carbon and low alloy steels, hardenability concepts based on austenite time-temperature transformation behavior can be effectively used to establish acceptable and unacceptable HTPQ pre-qualification ranges for carbon and low alloy steels. However, similar heat treatability concepts have not been effectively developed for high alloy steels. Therefore another method must be used to develop HTPQ guidelines for high alloy steels that permit successful HTPQ testing of a high alloy grade of material to pre-qualify other high alloy grades of material that are less difficult to solutionize and quench.

A survey listing the various cast high alloy steels was sent to Steel Founders Society of America members asking for feedback on the difficulties of solutionizing and quenching the high alloy and nickel-base cast alloy grades. Eight surveys were completed and returned. Tables XI through XVI show the average of the usable returned responses, grouped by alloy grades. The alloys are qualified based on their HTPQ rankings, not on the average scores calculated and presented.

Table XI: Survey Responses from SFSA Member Foundries for Austenitic Grades

AUSTENITIC GRADES	**Average Ease of Solutionizing Score**	**Ease of Solutionizing Ranking for HTPQ**	**Average Ease of Quenching Score**	**Ease of Quenching Ranking for HTPQ**
CE-30	4.0	A	3.5	A
CF-16Fa	4.0	A	3.4	A
CF-16F	4.0	A	3.4	A
CF-20	4.0	A	3.2	B
CF10SMnN	3.8	B	3.2	B
CF-8	3.8	B	3.1	B
CF-8C	3.8	B	2.9	C
CF-3	3.6	B	2.9	C
CG-12	3.5	B	2.8	C
CF-3M	3.4	C	3.2	B
CF-8M	3.4	C	3.1	B
CF3MN	3.3	D	2.9	C
CG6MMN	3.0	D	2.6	C
CG-3M	3.0	D	2.4	D
CG-8M	3.0	D	2.3	D

Score: larger numbers indicate alloys that are easier to quench/solutionize
Rankings: A is easiest to quench or solutionize, D is most difficult to quench/solutionize

Table XII: Survey Responses from SFSA Member Foundries for Duplex Grades

DUPLEX GRADES	**Average Ease of Solutionizing Score**	**Ease of Solutionizing Ranking for HTPQ**	**Average Ease of Quenching Score**	**Ease of Quenching Ranking for HTPQ**
CD-4MCu	2.5	A	2.1	C
A890-2A	2.4	A	2.8	A
A890-3A	2.4	A	2.8	A
A890-1B	2.4	A	2.5	B
A890-1A	2.4	A	2.4	B
A890-1C	2.1	B	2.6	A
A890-4A	1.8	B	2.8	A
A890-5A	1.5	C	1.9	C
A890-6A	1.1	C	1.6	C

Score: larger numbers indicate alloys that are easier to quench/solutionize
Rankings: A is easiest to quench or solutionize, C is most difficult to quench/solutionize

Table XIII: Survey Responses from SFSA Member Foundries for Ferritic Grades

FERRITIC GRADES	**Average Ease of Solutionizing Score**	**Ease of Solutionizing Ranking for HTPQ**	**Average Ease of Quenching Score**	**Ease of Quenching Ranking for HTPQ**
CB-6	3.5	A	3.3	A
CB-30	3.3	B	3.3	A
CC-50	3.3	B	2.8	B

Score: larger numbers indicate alloys that are easier to quench/solutionize
Rankings: A is easiest to quench or solutionize, C is most difficult to quench/solutionize

Table XIV: Survey Responses from SFSA Member Foundries for Martensitic Grades

MARTENSITIC GRADES	**Average Ease of Solutionizing Score**	**Ease of Solutionizing Ranking for HTPQ**	**Average Ease of Quenching Score**	**Ease of Quenching Ranking for HTPQ**
CA-15M	3.3	A	3.0	B
CA-6NM	3.2	A	3.3	B
CA-40F	3.0	A	3.0	B
CA-15	2.8	B	2.7	C
CA-28MWV	2.5	B	4.0	A
CA-6N	2.5	B	3.2	B
CA-40	2.4	C	2.0	B

Score: larger numbers indicate alloys that are easier to quench/solutionize
Rankings: A is easiest to quench or solutionize, C is most difficult to quench/solutionize

Table XV: Survey Responses from SFSA Member Foundries for Superaustenitic Grades

SUPERAUSTENITIC GRADES	Average Ease of Solutionizing Score	Ease of Solutionizing Ranking for HTPQ	Average Ease of Quenching Score	Ease of Quenching Ranking for HTPQ
CH8	4.0	A	3.5	A
CH-10	4.0	A	3.3	A
CF10	4.0	A	3.3	A
CH-20	3.7	A	3.5	A
CF10SMnN	3.7	A	3.5	A
CF10M	3.7	A	3.0	B
CK-20	3.2	B	3.5	A
CF10MC	3.0	B	2.6	B
CE20N	2.7	B	3.0	B
CN-7M	1.7	C	2.4	C
CK-3MCuN	1.3	C	1.5	D
CN-7MS	1.0	D	1.6	D
CN3M	0.8	D	2.1	C
CN-3MN	0.7	D	2.0	C
CK-35MN	0.3	D	1.9	D
CT15C	-	-	2.0	C

Score: larger numbers indicate alloys that are easier to quench/solutionize
Rankings: A is easiest to quench or solutionize, D is most difficult to quench/solutionize

Table XVI: Survey Responses from SFSA Member Foundries for Nickel Grades

NICKEL GRADES	Average Ease of Solutionizing Score	Ease of Solutionizing Ranking for HTPQ	Average Ease of Quenching Score	Ease of Quenching Ranking for HTPQ
Inconel 685	3.0	A	-	-
CY40	2.2	A	2.8	A
Inconel 601	2.0	A	3.0	A
Inconel 617	2.0	A	3.0	A
M-25S	2.0	A	2.5	B
CU5MCuC	2.0	A	2.3	B
N12MV	1.7	A	2.4	B
CW6M	1.5	B	2.4	B
N7M	1.5	B	2.4	B
Inconel 600	1.5	B	2.3	B
Inconel 625	1.5	B	2.3	B
CX2MW	1.2	B	2.0	C
CW2M	1.1	B	2.0	C
Inconel 689	1.0	C	-	-
CW-6MC	1.0	C	2.4	B
CW12MW	1.0	C	2.3	B
CX2M	0.5	D	2.0	C
Inconel 718	0.0	D	2.3	B
CZ100	-	-	4.0	A

Score: larger numbers indicate alloys that are easier to quench/solutionize
Rankings: A is easiest to quench or solutionize, D is most difficult to quench/solutionize

These semi-quantitative ease of heat treatment ranking combined with HTPQ section size information can be used to determine pre-qualified heat treatments for high alloys steels. This information is further described in Appendix C.

2.4 Hardenability of Carbon & Low Alloy Steels

2.4.1 Hardenability Concepts

Hardenability concepts can be effectively used to predict the heat treatment response of carbon and low alloy steels. Steel hardenability (ideal critical diameter) data can be combined with quench severity data to express the section size limits for successful heat treatment in terms of critical diameter or thickness. These robust concepts are the basis for quench & temper section size limits used by foundries for carbon and low alloy cast steel grades. Successful quenching also depends on adequate alloy composition control for the grade of steel being heat treated. Leaner compositions and lower carbon content heats within an alloy grade will have much lower hardenability than richer compositions. Figure 20 illustrates the variation in Jominy end-quench hardenability behavior for wrought 4130 steels with various compositions that are all within acceptable composition limits. Similarly, the hardenability behavior for C-Mn and low alloy cast steels, can be expected to show wide differences in heat treatment response depending on actual alloy compositions within an alloy grade.

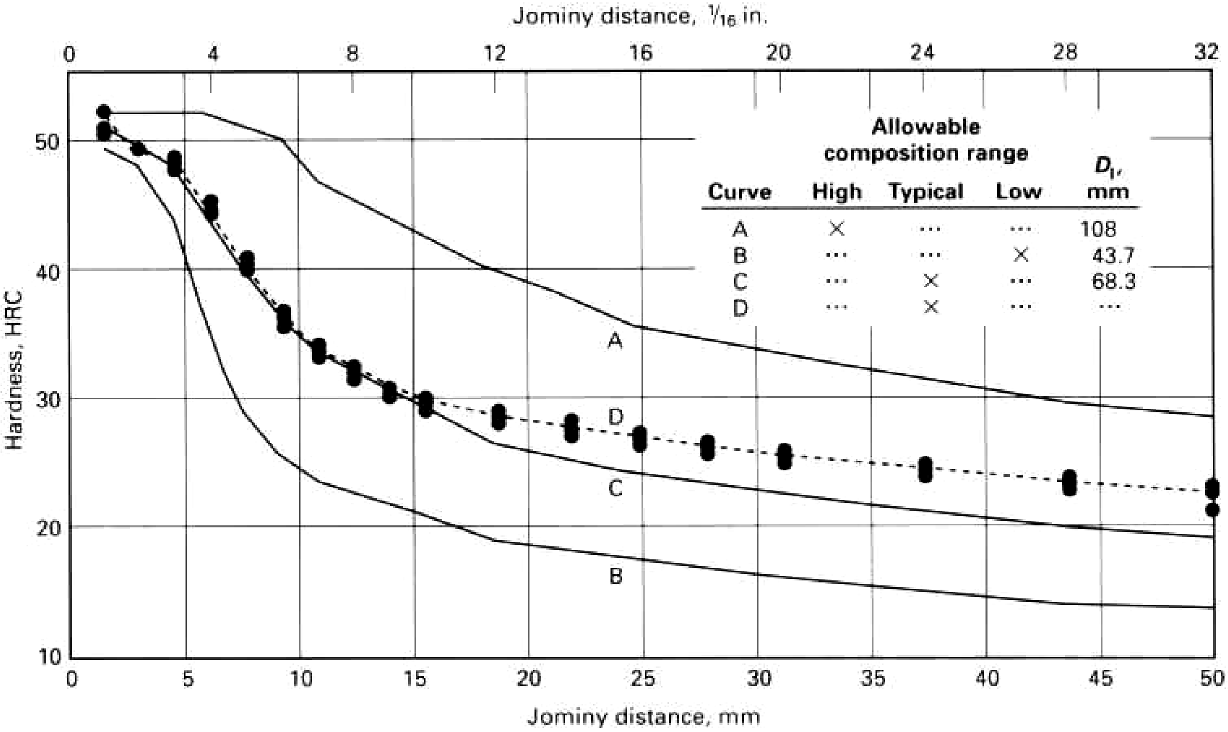


Figure 20: Calculated and experimental Jominy hardness values for AISI 4130 steel austenitized and quenched from 1575F. Curves A, B, C were calculated from D_I values; curve D was obtained from measured hardness values. [BATE1997]

Ideal Critical Diameter is a measure of the hardenability of a steel. It can be derived from Jominy end-quench testing and is defined as the diameter of a cylindrical bar that would have a 50% martensitic microstructure at its center under an ideal quench. An ideal quench is one where the surface of the bar is instantly cooled to the temperature of the quenchant [BRIG1970]. Ideal Critical Diameter provides a useful basis for the comparison of hardenability among many different alloys.

Ideal Critical Diameter of a steel can be estimated from the composition of alloying elements in that particular steel. Tables XVII and XVIII from the SFSA Steel Heat Treatment Handbook (Supplement 11) [SFSA1985] can be used for these calculations. Hardenability factors from Table XVII are recorded for each alloying element/composition combination. The combined sum of all of these hardenability factors is then used in conjunction with Table XVIII to determine the Ideal Critical Diameter (D_I) of the steel. Once determined, the D_I values can be used for comparisons among steels for use in HTPQ determination.

Table XVII: Individual alloying element hardenability factors (D_I Factors) used for overall alloy D_I calculation [1] [SFSA1985]

	Alloy D_I Factors						
%Element	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Cu**	**Mo**
.20	0.1458	0.2227	0.0569	0.1556	0.0306	0.0306	0.2041
.25	0.1929	0.2636	0.0700	0.1875	0.0378	0.0378	0.2430
.30	0.2317	0.3010	0.0828	0.2170	0.0453	0.0453	0.2788
.35	0.2658	0.3306	0.0952	0.2445	0.0523	0.0523	0.3118
.40	0.2967	0.3677	0.1072	0.2705	0.0592	0.0592	0.3424
.45	0.3222	0.3976	0.1189	0.2949	0.0663	0.0663	0.3711
.50	0.3444	0.4255	0.1303	0.3181	0.0730	0.0730	0.3979
.55	0.3614	0.4518	0.1415	0.3403	0.0795	0.0795	
.60	0.3838	0.4767	0.1523	0.3610	0.0860	0.0860	
.65		0.5001	0.1629	0.3811	0.0924	0.0924	
.70		0.5226	0.1732	0.4000	0.0986	0.0986	
.75		0.5437	0.1833	0.4185	0.1052	0.1052	
.80		0.5640	0.1931	0.4358	0.1109	0.1109	
.85		0.5831	0.2028	0.4528	0.1169	0.1169	
.90		0.6017	0.2122	0.4689	0.1229	0.1229	
.95		0.6192	0.2214	0.4847	0.1284	0.1284	
1.00		0.6368	0.2305	0.4997	0.1339	0.1339	
1.05		0.6531	0.2393	0.5142	0.1399	0.1399	
1.10		0.6688	0.2480	0.5284	0.1461	0.1461	
1.15		0.6840	0.2565	0.5422	0.1517	0.1517	
1.20		0.6986	0.2648	0.5553	0.1569	0.1569	
1.25		0.7199	0.2730	0.5683	0.1626	0.1626	
1.30		0.7401	0.2810	0.5807	0.1679	0.1679	
1.35		0.7593	0.2889	0.5930	0.1735	0.1735	
1.40		0.7779	0.2967	0.6047	0.1790	0.1790	
1.45		0.7961	0.3043	0.6163	0.1847	0.1847	
1.50		0.8137	0.3118	0.6274	0.1901	0.1901	
1.55		0.8304	0.3191	0.6384	0.1967	0.1967	
1.60		0.8464	0.3263	0.6490	0.2030	0.2030	
1.65		0.8625		0.6594	0.2093	0.2093	
1.70		0.8777		0.6695	0.2151	0.2151	
1.75		0.8923		0.6795	0.2217	0.2217	
1.80		0.9064		0.6891	0.2279	0.2279	
1.85		0.9199		0.6987	0.2335	0.2335	
1.90		0.9303		0.7079	0.2430	0.2430	
1.95		0.9440		0.7171	0.2453	0.2453	
2.00		0.9584		0.7259	0.2499	0.2499	
2.05					0.2560	0.2560	
2.10					0.2620	0.2620	
2.15					0.2686	0.2686	
2.20					0.2751	0.2751	
2.25					0.2817	0.2817	
2.30					0.2880	0.2880	
2.35					0.2956	0.2956	
2.40					0.3030	0.3030	
2.45					0.3107	0.3107	
2.50					0.3181	0.3181	

[1] Total alloy D_I is obtained by summing the individual Alloy D_I factors and combining with values from Table XVIII

Table XVIII: Steel alloy D_I based on the sum of individual alloy factors from Table XVII [SFSA1985]

Sum of Alloy Factors	Ideal Critical Diameter (D_I)
1.00	1.00
1.01	1.02
1.02	1.05
1.03	1.07
1.04	1.10
1.05	1.12
1.06	1.15
1.07	1.18
1.08	1.20
1.09	1.23
1.10	1.26
1.11	1.29
1.12	1.32
1.13	1.35
1.14	1.38
1.15	1.41
1.16	1.44
1.17	1.48
1.18	1.51
1.19	1.55
1.20	1.59
1.21	1.62
1.22	1.66
1.23	1.70
1.24	1.74
1.25	1.78
1.26	1.82
1.27	1.86
1.28	1.90
1.29	1.95
1.30	2.00
1.31	2.04
1.32	2.09
1.33	2.14
1.34	2.19
1.35	2.24
1.36	2.29
1.37	2.34
1.38	2.40
1.39	2.46
1.40	2.51
1.41	2.57
1.42	2.63
1.43	2.69
1.44	2.75
1.45	2.82
1.46	2.88
1.47	2.95
1.48	3.02
1.49	3.09
1.50	3.16
1.51	3.24
1.52	3.31
1.53	3.39
1.54	3.47
1.55	3.55
1.56	3.63
1.57	3.72
1.58	3.80
1.59	3.89
1.60	3.98
1.61	4.07
1.62	4.17
1.63	4.27
1.64	4.37
1.65	4.47
1.66	4.57
1.67	4.68
1.68	4.79
1.69	4.90
1.70	5.01
1.71	5.13
1.72	5.25
1.73	5.37
1.74	5.50
1.75	5.62
1.76	5.75
1.77	5.89
1.78	6.03
1.79	6.17
1.80	6.31
1.81	6.46
1.82	6.61
1.83	6.76
1.84	6.92
1.85	7.08
1.86	7.24
1.87	7.41

2.4.2 Use of Hardenability Concepts for Heat Treatment Procedure Qualification of Carbon & Low Alloy Steels

The interaction between quenching performance and alloy hardenability is at the center of HTPQ methodology development for carbon and low alloy steels. Successful demonstration of heat treatment success during HTPQ testing for one particular alloy composition and section size at a given set of quenching conditions can be extended to other alloy compositions and section sizes requiring less quench severity for successful heat treatment. Successful qualification of a given alloy composition and section size can be used to define an effective HTPQ quench severity based on the classical work of Grossman and Bain [GROS1964], Figure 21. Figure 22 shows that the ideal critical diameter can also be expressed as the critical section thickness in the case of plate-shaped casting sections. Based on this HTPQ quench severity determination from a successful HTPQ test, other combinations of alloy composition and section sizes requiring lesser quench severities can be considered to be HTPQ pre-qualified.

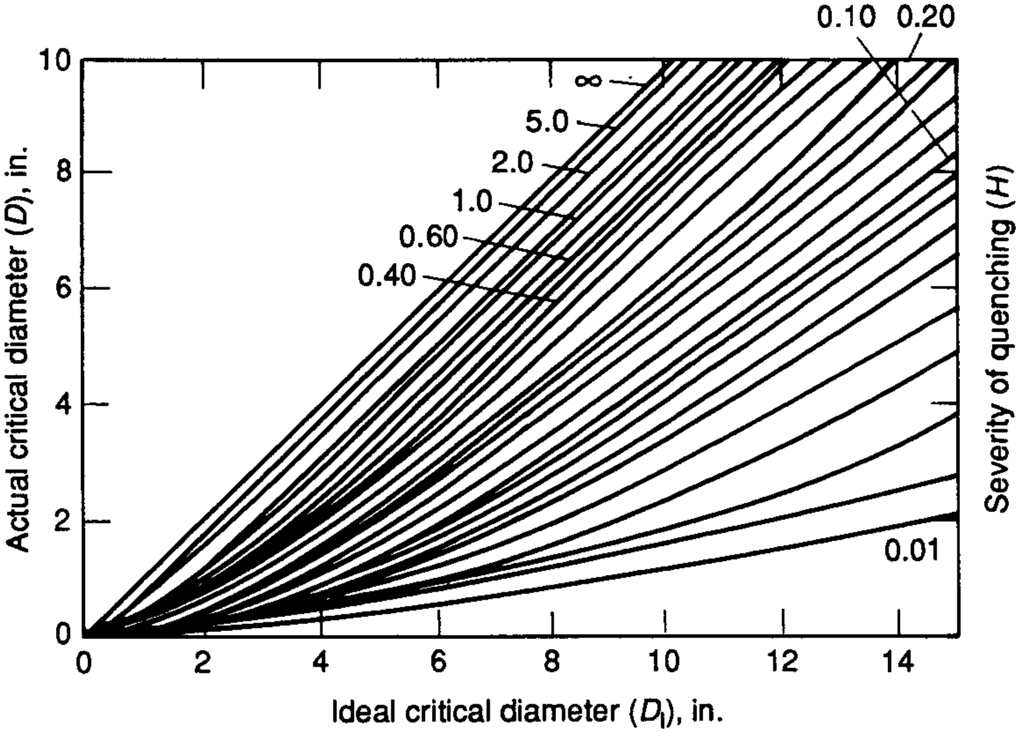


Figure 21: Fundamental relationship among ideal critical diameter, actual critical diameter, and severity of quenching [TOTT1993]

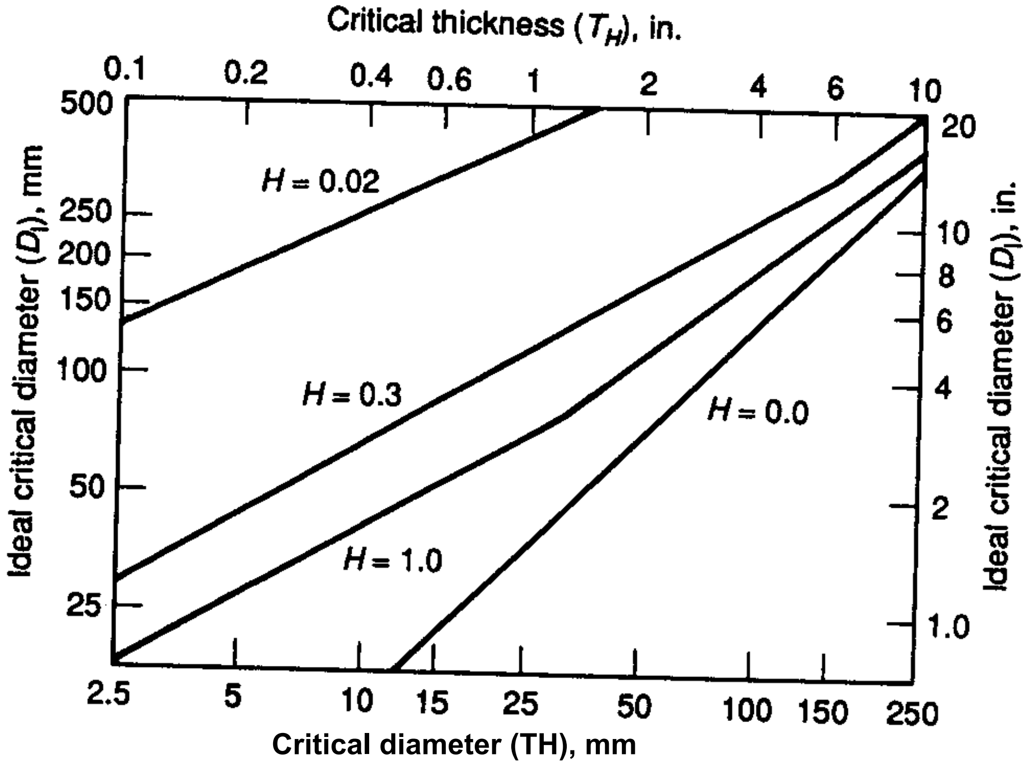


Figure 22: Relationship between ideal critical diameter and the critical thickness that can be fully hardened using a quenching medium with quench severity H [TOTT1993]

This pre-qualification method, based on hardenability and quench severity, is illustrated directly in Figures 23 and 24. Ideal Critical Diameter, based on alloy composition, has been plotted against the HTPQ bar diameter, D, that can be successfully heat treated at different quench severity values. A successful HTPQ test of a given section size (horizontal line) and alloy composition D_I (vertical line) define a given quench severity for a foundry's quenching system. Successful heat treatment of other combinations of section size and composition can be expected as long as they require an effective quench severity that is less than or equal to the effective quench severity from a successful HTPQ test.

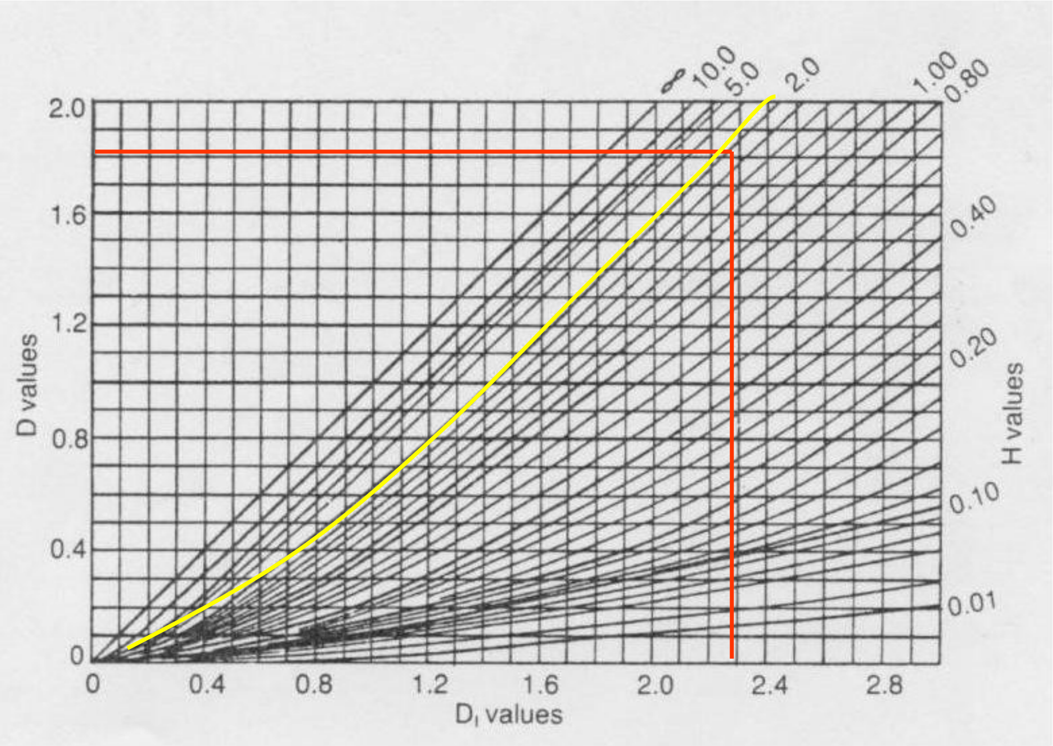


Figure 23: Plots of D_I (inches) versus equivalent casting section diameter for prequalification schema

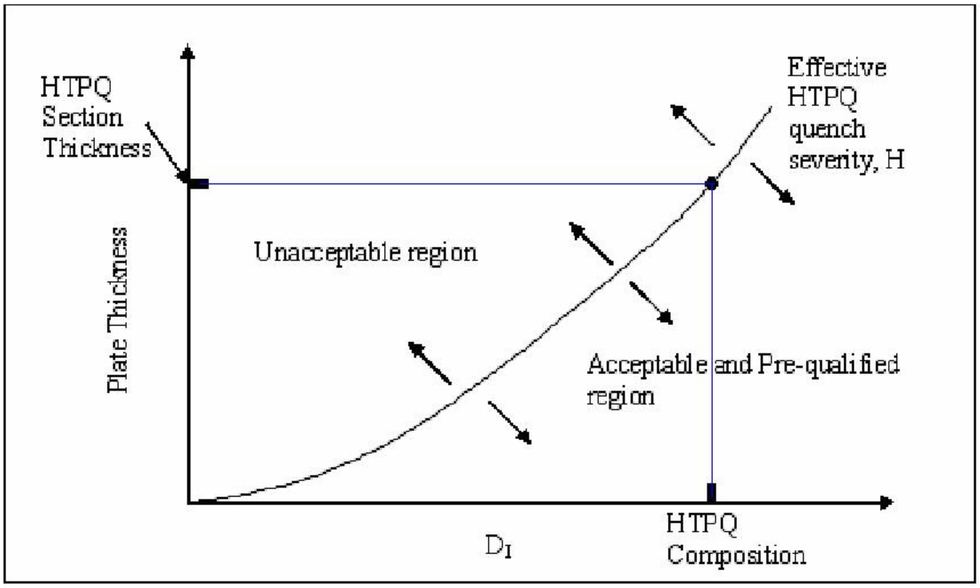


Figure 24: Schematic representation of HTPQ "acceptable and pre-qualified" regions based on hardenability concepts for carbon and low alloy steels

HTPQ test specimen section size from a successful HTPQ test together with the overall D_I value for that material can be used to determine other alloy D_I and section sizes that are pre-qualified. Figure 23 and Figure 25 can be used to determine these other alloy and section size combinations. Figure 26 is similar to Figure 25, except that it uses HTPQ section diameter rather than section thickness. The calculated Ideal Critical Diameter of the alloy qualified and the section thickness qualified indicate the effective severity of the quench during qualification testing. All combinations of alloy D_I values and section sizes with lesser quench severity than for the successful HTPQ test are pre-qualified.

		HTPQ Section Thickness (in)							
		0.25	**0.5**	**1**	**2**	**3**	**4**	**6**	**10**
	15	0.00	0.00	0.01	0.02	0.03	0.04	0.06	0.29
	14	0.00	0.00	0.01	0.02	0.04	0.05	0.11	0.73
	13	0.00	0.00	0.01	0.02	0.04	0.06	0.16	0.68
	12	0.00	0.00	0.01	0.03	0.05	0.08	0.22	1.14
Overall Ideal Critical Diameter D_I(in)	**11**	0.00	0.00	0.01	0.04	0.06	0.09	0.26	1.11
	10	0.00	0.00	0.02	0.04	0.08	0.15	0.44	2.17
	9	0.00	0.00	0.02	0.06	0.10	0.17	1.75	∞
	8	0.00	0.01	0.03	0.07	0.15	0.32	∞	
	7	0.00	0.02	0.04	0.11	0.25	0.55		
	6	0.00	0.02	0.05	0.17	0.38	2.59		
	5	0.00	0.02	0.09	0.34	1.01	∞		
	4	0.00	0.05	0.14	0.62	∞			
	3	0.04	0.12	0.35	2.30				
	2	0.13	0.37	1.52	∞				
	1	0.72	2.29	∞					

Effective HTPQ
Quench Severity
Grossman Number (H)

Figure 25: Effective HTPQ Quench Severity Values as a function of overall alloy D_I and the HTPQ section thickness. Successful HTPQ at an effective HTPQ quench severity value prequalifies other alloy (D_I) and section size combinations with equal or lower effective HTPQ quench severity values.

		HTPQ diameter(in)									
		0.25	**0.5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	15	0.00	0.00	0.01	0.01	0.02	0.03	0.04	0.04	0.05	0.06
	14	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.06	0.08	0.10
	13	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.08	0.11	0.15
	12	0.00	0.00	0.01	0.02	0.03	0.05	0.06	0.09	0.14	0.21
Overall Ideal Critical Diameter D_I(in)	**11**	0.00	0.00	0.01	0.02	0.04	0.06	0.08	0.11	0.16	0.24
	10	0.00	0.00	0.01	0.03	0.05	0.08	0.12	0.19	0.28	0.42
	9	0.00	0.00	0.01	0.04	0.07	0.09	0.13	0.21	0.32	1.33
	8	0.00	0.01	0.02	0.05	0.09	0.14	0.24	0.46	1.16	9.38
	7	0.00	0.01	0.03	0.07	0.13	0.23	0.38	1.15	7.99	∞
	6	0.00	0.01	0.03	0.10	0.20	0.38	0.78	7.70	∞	
	5	0.00	0.01	0.05	0.15	0.39	0.76	6.69	∞		
	4	0.00	0.02	0.10	0.33	0.82	8.14	∞			
	3	0.02	0.08	0.20	0.84	3.42	∞				**Effective HTPQ**
	2	0.08	0.28	0.58	10.24	∞					**Quench Severity**
	1	0.50	1.48	6.15	∞						**Grossman Number (H)**

Figure 26: Effective HTPQ Quench Severity Values as a function of overall alloy D_I and the HTPQ diameter. Successful HTPQ at an effective HTPQ quench severity value prequalifies other alloy (D_I) and section size combinations with equal or lower effective HTPQ quench severity values.

2.4.3 Hardenability Concepts for HTPQ of Carbon and Low Alloy Steels—An Example.

The use of this HTPQ pre-qualification scheme is demonstrated for HTPQ results developed during this research. For example, consider an alloy composition such as 8625, Table XIX. From HTPQ trials, it has been shown that one inch section sizes of this alloy can be successfully heat treated.

Table XIX: Example composition of 8625 steel

%C	%Mn	%S	%Ni	%Si	%Cr	%Mo	%P
0.25	0.75	0.04	0.55	0.70	0.55	0.25	0.04

Figures 27 and 28 illustrate alloy D_I determination for this 8625 steel. The applicable values are highlighted with bold print. The values from Figure 27 are summed and applied to Figure 28.

Percentage of Element	C	Mn	Si	Cr	Ni	Cu	Mo
.20	0.1458	0.2227	0.0569	0.1556	0.0306	0.0306	0.2041
.25	**0.1929**	0.2636	0.0700	0.1875	0.0378	0.0378	**0.2430**
.30	0.2317	0.3010	0.0828	0.2170	0.0453	0.0453	0.2788
.35	0.2658	0.3306	0.0952	0.2445	0.0523	0.0523	0.3118
.40	0.2967	0.3677	0.1072	0.2705	0.0592	0.0592	0.3424
.45	0.3222	0.3976	0.1189	0.2949	0.0663	0.0663	0.3711
.50	0.3444	0.4255	0.1303	0.3181	0.0730	0.0730	0.3979
.55	0.3614	0.4518	0.1415	**0.3403**	**0.0795**	0.0795	
.60	0.3838	0.4767	0.1523	0.3610	0.0860	0.0860	
.65		0.5001	0.1629	0.3811	0.0924	0.0924	
.70		0.5226	**0.1732**	0.4000	0.0986	0.0986	
.75		**0.5437**	0.1833	0.4185	0.1052	0.1052	
.80		0.5640	0.1931	0.4358	0.1109	0.1109	
.85		0.5831	0.2028	0.4528	0.1169	0.1169	
.90		0.6017	0.2122	0.4689	0.1229	0.1229	
.95		0.6192	0.2214	0.4847	0.1284	0.1284	
1.00		0.6368	0.2305	0.4997	0.1339	0.1339	

Figure 27: Example alloy D_I factors for an 8625 steel. The sum of the alloy factors is 1.3994. (.1929 + .5437 + .1732 + .3403 + .0795 + .2430 = 1.5726)

Sum of Alloy Factors	Ideal Critical Diameter (D_I)
1.44	2.75
1.45	2.82
1.46	2.88
1.47	2.95
1.48	3.02
1.49	3.09
1.50	3.16
1.51	3.24
1.52	3.31
1.53	3.39
1.54	3.47
1.55	3.55
1.56	3.63
1.57	**3.72**
1.58	3.80
1.59	3.89
1.60	3.98
1.61	4.07
1.62	4.17
1.63	4.27
1.64	4.37

Figure 28: Alloy D_I determination for an 8625 steel

Knowing that this material (D_I of 3.72) was HTPQ qualified in a 1.0 inch thick section, other alloy D_I and section size combinations that are prequalified can be determined as shown in Figure 29. The values in italics and bounded by the black border are HTPQ quench severity values corresponding to the pre-qualified alloy D_I and section thickness combination.

		HTPQ Section Thickness (in)							
		0.25	**0.5**	**1**	**2**	**3**	**4**	**6**	**10**
	15	*0.00*	*0.00*	*0.01*	*0.02*	*0.03*	*0.04*	*0.06*	0.29
	14	*0.00*	*0.00*	*0.01*	*0.02*	*0.04*	*0.05*	*0.11*	0.73
	13	*0.00*	*0.00*	*0.01*	*0.02*	*0.04*	*0.06*	0.16	0.68
	12	*0.00*	*0.00*	*0.01*	*0.03*	*0.05*	*0.08*	0.22	1.14
Overall Ideal Critical Diameter D_I(in)	**11**	*0.00*	*0.00*	*0.01*	*0.04*	*0.06*	*0.09*	0.26	1.11
	10	*0.00*	*0.00*	*0.02*	*0.04*	*0.08*	0.15	0.44	2.17
	9	*0.00*	*0.00*	*0.02*	*0.06*	*0.10*	0.17	1.75	∞
	8	*0.00*	*0.01*	*0.03*	*0.07*	0.15	0.32	∞	
	7	*0.00*	*0.02*	*0.04*	*0.11*	0.25	0.55		
	6	*0.00*	*0.02*	*0.05*	0.17	0.38	2.59		
	5	*0.00*	*0.02*	*0.09*	0.34	1.01	∞		
	4	*0.00*	*0.05*	*0.14*	0.62	∞			
	3	*0.04*	*0.12*	0.35	2.30				
	2	*0.13*	0.37	*1.52*	∞				
	1	0.72	2.29	∞					

Effective HTPQ Quench Severity Grossman Number (H)

Figure 29: Prequalified D_I and section thickness combinations for an 8625 steel. All combinations represented by values upwards and to the left of the bounding lines are pre-qualified.

2.4.4 Alternate HTPQ scheme based on Quenched Hardness

Another HTPQ qualification method requiring no furnace instrumentation is to qualify all heat treated castings based on the minimum quenched hardness that is a function of carbon content only. The quenched hardness of steels varies as a function of percent martensite and carbon content as shown in Figure 30. Values from the region bounded by curves representing 95% martensite and 90% martensite in Figure 31 and within the range of hardnesses commonly achieved in industry, shown in Figure 32, were used to choose appropriate minimum quenched hardness values for HTPQ as shown in Table XX. Because of the direct relationship between martensite hardness and alloy carbon content, it is possible to also use quenched hardness values as an alternate indication of heat treatment qualification success. This method of HTPQ requires no heat treatment time and temperature documentation. Rather, it requires demonstration of the quenched hardness of a particular section size of a casting to demonstrate successful heat treatment. This qualification scheme is referred to as Procedure C in the specification drafts (Appendix B) and will be referred to as “HTPQ Method C” for the remainder of this document.

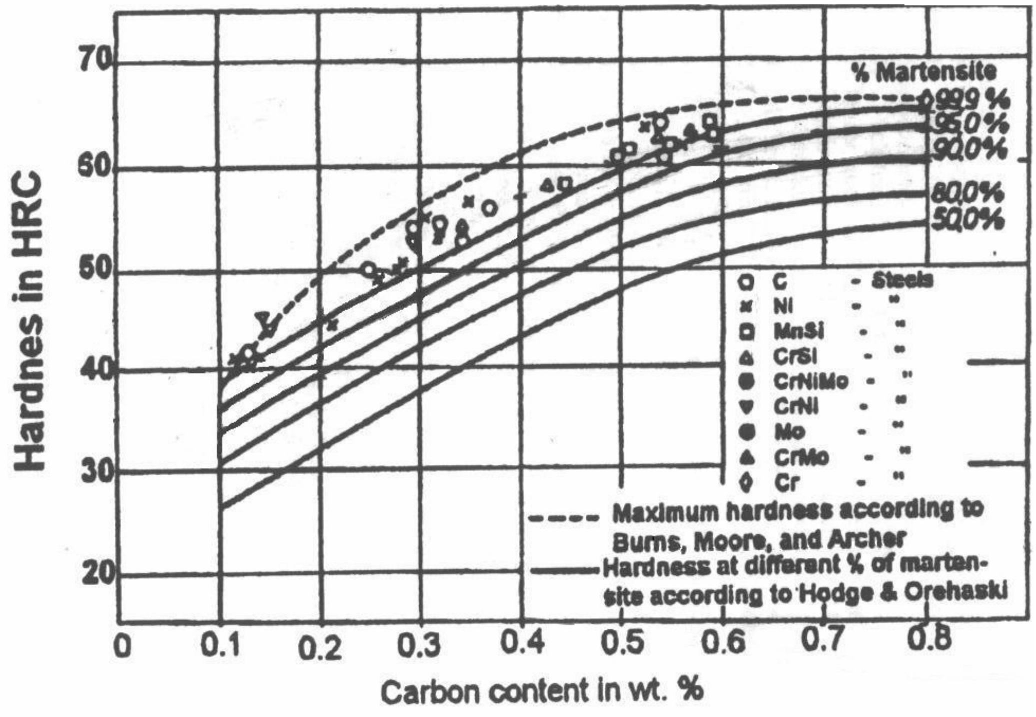


Figure 30: Hardness of martensite as a function of carbon content [TOTT1997]

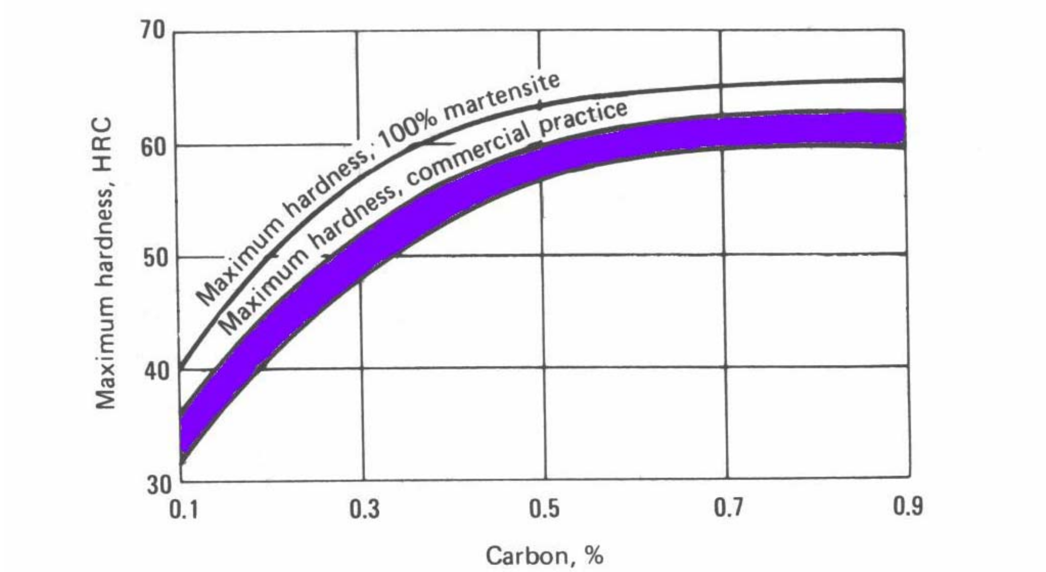


Figure 31: Hardness of martensite as a function of carbon content. The blue band represents commonly achieved industry values. [CHAN1995]

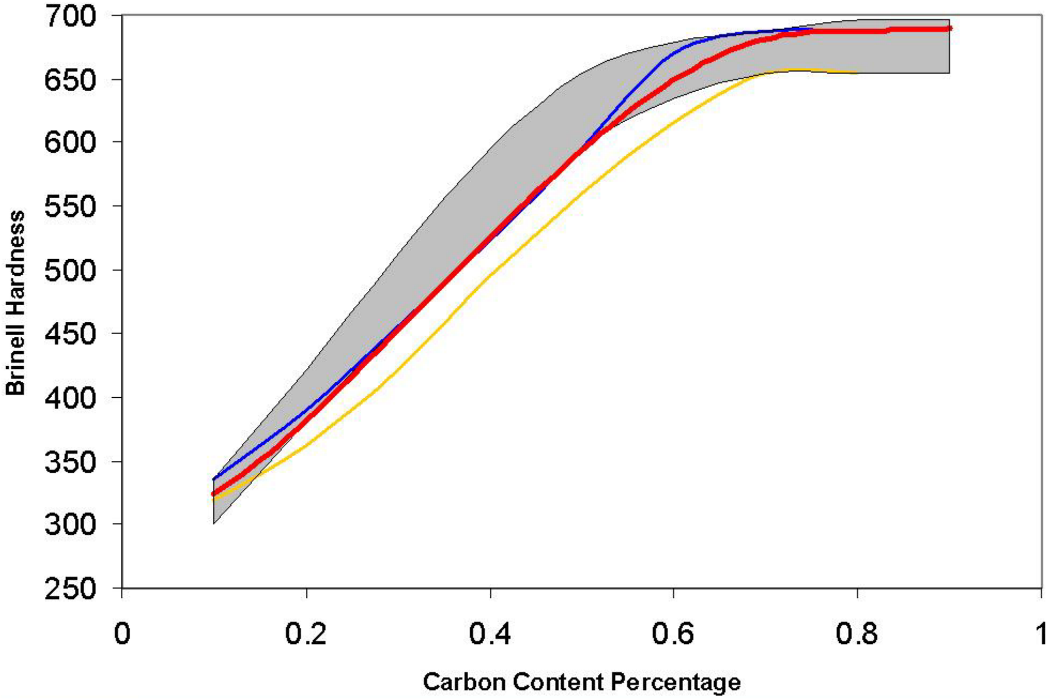


Figure 32: As-quenched hardness as a function of carbon content of martensite [CHAN1995], [KRAU1978]. The gray field represents commonly achieved industry values; the blue and gold lines represent 95% and 90% martensite, respectively. The red line is the recommended minimum quenched hardness for HTPQ Method C.

Table XX: Minimum quenched hardness values for acceptable HTPQ of carbon and low alloy steels based on alloy carbon content

Percent Carbon Content	Quenched Surface Hardness (HB)
0.10	325
0.11	329
0.12	334
0.13	339
0.14	345
0.15	350
0.16	356
0.17	362
0.18	369
0.19	375
0.20	382
0.21	389
0.22	396
0.23	402
0.24	410
0.25	417
0.26	424
0.27	431
0.28	438
0.29	446
0.30	453
0.31	460
0.32	467
0.33	475
0.34	482
0.35	489
0.36	497
0.37	504
0.38	511
0.39	518
0.40	526
0.41	533
0.42	540
0.43	547
0.44	554
0.45	561
0.46	568
0.47	574
0.48	581
0.49	587
0.50	594
0.51	600
0.52	606
0.53	612
0.54	618
0.55	624
0.56	629
0.57	635
0.58	640
0.64	665
0.65	669
0.66	672
0.67	674
0.68	677
0.69	679
0.70	681
0.71	683
0.72	684
0.73	685
0.74	686
0.75	687
0.76	687
0.77	688
0.78	688
0.79	688
0.80	688
0.81	688
0.82	688
0.83	688
0.84	689
0.85	689
0.86	689
0.87	689
0.88	689
0.89	689
0.90	690

2.5 Tempering of Carbon & Low Alloy Steels

2.5.1 Tempering Time and Temperature

Tempering times and temperatures are chosen by the foundry to target the final properties of carbon and low alloy cast steel grades. Figure 33 shows a characteristic tempering time-temperature map for a 4340 wrought steel. A wide range of acceptable tempering temperatures and times can be selected to achieve final properties for a given cast steel alloy. Similarly, a given cast steel composition can often be heat treated to produce different grades of material simply by adjusting the tempering time and temperature. In practice, tempering temperature has a much more dominant effect on tempered hardness than tempering time. The influence of tempering temperature on the mechanical properties of a typical wrought low alloy steel can be seen in Figure 34. It can be seen that as temperature increases, hardness, tensile strength, and yield strength decrease, while ductility and toughness increase.

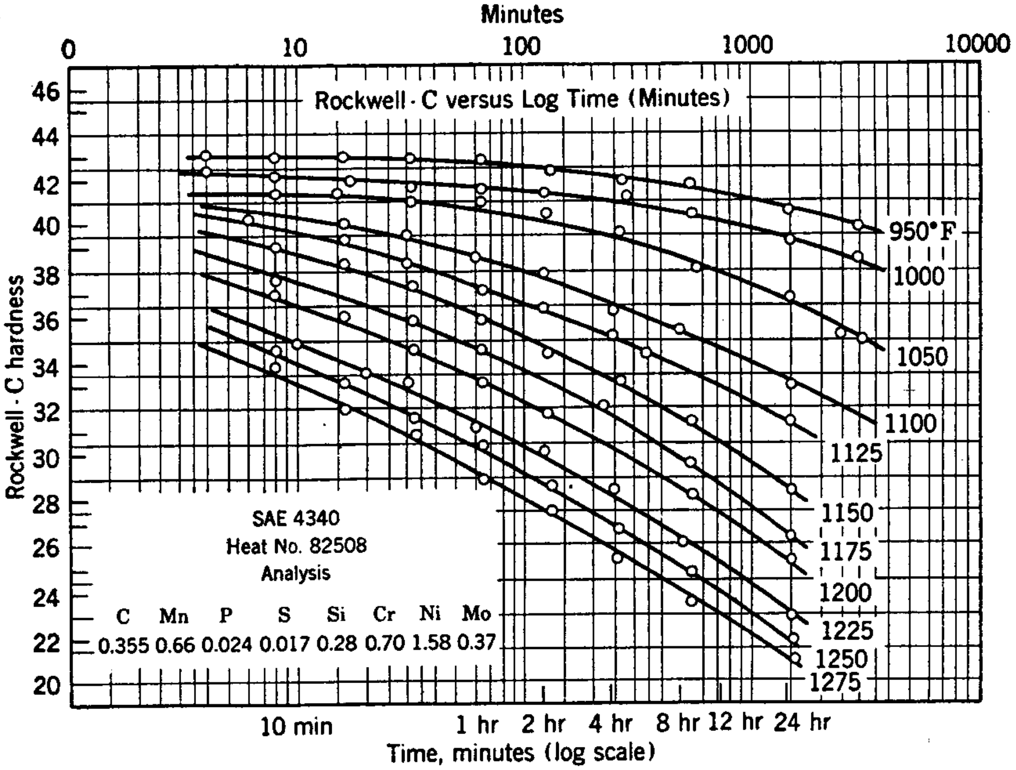


Figure 33: Tempering response of a wrought SAE 4340 steel for quench & temper heat treatments [BULL1948]

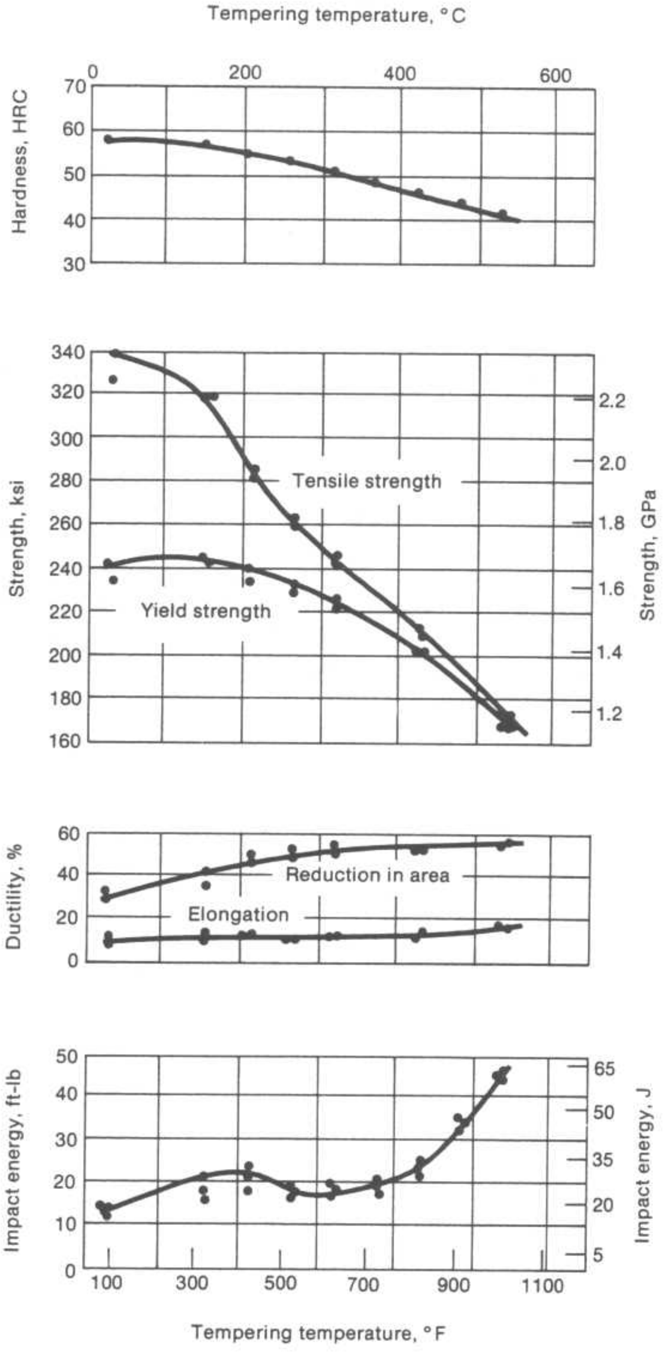


Figure 34: Mechanical properties of a 4340 wrought steel oil quenched to produce a martensitic structure and tempered for 1 hour at various tempering temperatures [SEMI1986]

Alloying elements in steels not only promote hardenability during austenitizing and quenching, but also contribute to resistance to softening during tempering. Therefore tempering times and temperatures used by a foundry can be expected to be somewhat alloy dependent. The influence of carbon content on the quenched & tempered hardness of C-Mn wrought steels as a function of temperature can be seen in Figure 35.

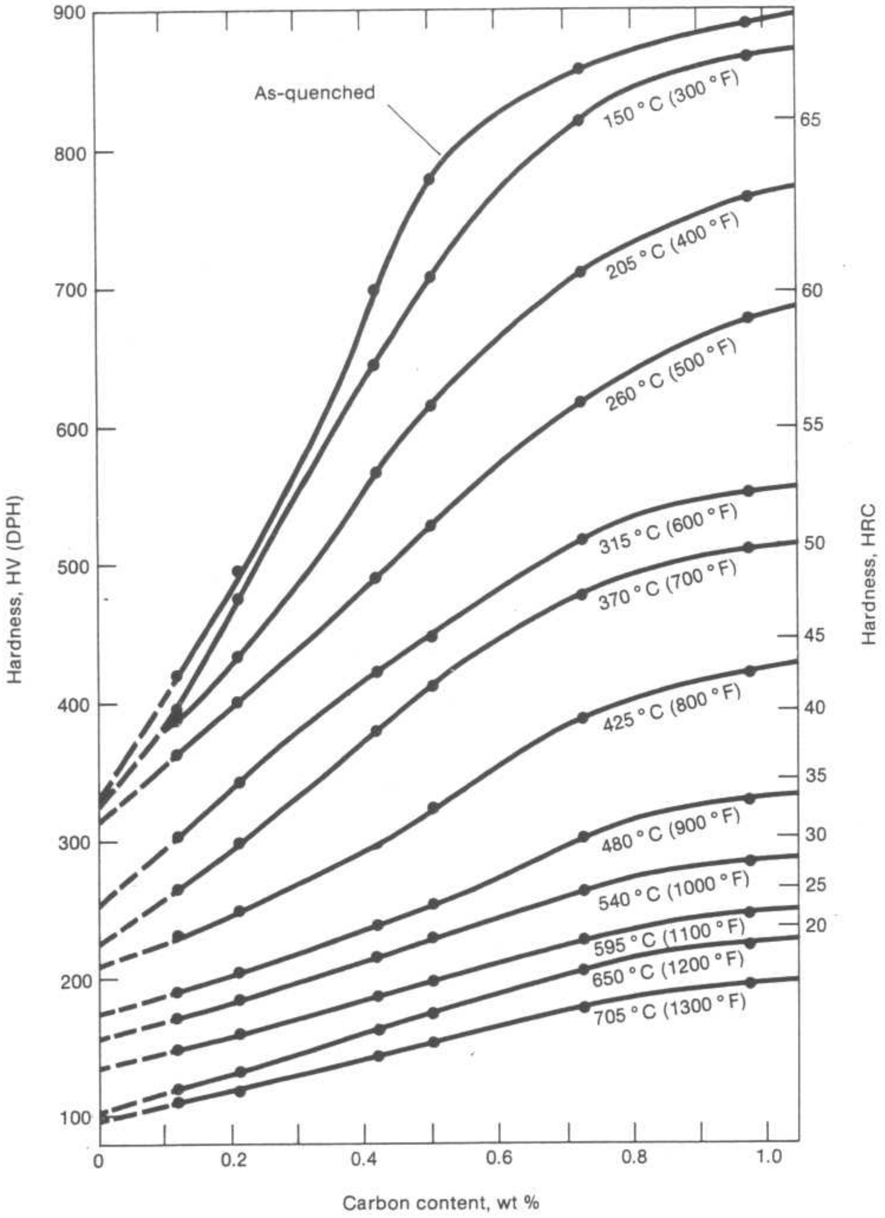


Figure 35: Quenched & tempered hardness as a function of carbon content for iron-carbon alloys tempered at various temperatures [SEMI1986]

Temperature variations within tempering furnaces due to lack of temperature uniformity can be expected to influence the hardness of castings depending on their position in the furnace. Table XXI illustrates simple estimates of the influence of tempering furnace tempering temperature uniformity on the expected final hardness variations after a quench & temper heat treatment for an 8630 steel. Large temperature variations can be expected to lead to unacceptably large variations in final hardness after tempering. However, variations in final tempered hardness due to furnace temperature variations are only a small part of the overall tempering control issue.

Table XXI: Tempered hardness variations due to tempering temperature variations for 8630 steel of nominal composition. Estimated with the Creusot Loire tempering model [MAYN1978]. The tempering temperature is 1150F.

Variation in set-point temperature	**Expected variation in Tempered hardness**
+/- 10F	+/- 3.5HB
+/- 15F	+/- 4.5HB
+/- 25F	+/- 7HB
+/- 50F	+/- 6HB
+/- 100F	+/- 39HB

Because control of tempering time and temperature are critical to the properties of a steel casting, steel foundries wishing to control final tempered hardness face the same temperature uniformity and temperature ramp-up issues discussed previously during austenitizing. However, one aspect of tempering control is even more problematic. Proper austenitizing still occurs when actual austenitizing times and temperatures exceed the minimum temperature and time requirements for successful austenitizing. However, during tempering either insufficient tempering time/temperature or excessive tempering time/temperature will adversely affect control of properties after tempering. Variations in ramp-up time during tempering can also be expected to influence the extent of tempering.

Even more important than ramp-up time during tempering is the influence of alloying elements on the tempering response of cast steel alloys. Most common alloying elements promote tempering resistance in steels. This tempering resistance not only results in different tempering responses for different grades of material, but also in differing tempering responses for a given grade of material due to chemical composition variations.

Researchers have developed reasonable (but rarely used) models that can be used to predict the tempered hardness of steels as a function of composition, initial microstructure, tempering time and tempering temperature [BROO1996]. However, these models were developed from the tempering of small wrought steel samples heat treated for short periods of time. The tempering ramp-up and hold cycles typically used in steel foundries have not been previously modeled. Laboratory heat treatment studies of cast steels at Penn State have shown that wrought steel tempering models from the literature cannot be used to accurately predict cast steel tempered hardness values. However, they can be used to estimate the degree of heat treatment and composition control necessary to obtain consistent final tempered hardness.

2.5.2 Comparison of Tempering Models

Table XXII summarizes the capabilities of the various tempering models reported in the literature. Though finite difference methods [BROO1996] have the ability to incorporate ramp-up times, their drawback is that they predict properties based on activation energies, which are known for only certain grades of steel. Totten, et al. [TOTT1977] consider only tempering temperature and as-quenched hardness and therefore may not be useful for predicting final properties for many other heat treatment types used by steel foundries.

Table XXII: Comparison of tempering model characteristics

	Heat Treatment Factors Considered in the Tempering Models			
Model	**Tempering Hold Time**	**Ramp-up to tempering temperature**	**Metal Composition**	**Starting Microstructure**
Creusot Loire [MAYN1978]	Any time	Not Considered	Any composition	Any Microstructure
Grange Hribal Porter [GRAN1977]	1 hr	Not Considered	Any composition	Martensite
Crafts-Lamont [CRAF1947]	2 hrs	Not Considered	Any composition	Martensite
Spies et.al. [TOTT1977]	-	Not Considered	Any composition	Any Microstructure
Totten et al. [TOTT1977]	Any time	Not Considered	Alloy Grade	Martensite

Initial microstructure prior to tempering is a particularly important consideration for predicting the final tempered properties of steel castings. In heavy section steel castings, a 100% martensitic initial structure cannot always be guaranteed after quenching. Any other starting microstructures can be expected to have a different softening response during tempering. The Creusot Loire model [MAYN1978] explicitly calculates final tempered hardness values based on starting microstructures of 100% martensite, bainite or ferrite-pearlite structures. Hardness values for a combination of these structures can be estimated by applying a “rule of mixtures” concept. Spies et.al. [TOTT1977] also allow varying starting microstructures. However, their models require as-quenched hardness as an input to predict final tempered properties. The advantage of these models over the other empirical models is that they can potentially take into consideration the effect of section size, even though this is done indirectly.

Assessment of the tempering models contained in the literature indicate that the Grange, Hribal, and Porter [GRAN1977], and the Spies model [TOTT1977] cannot be effectively used to model steel casting tempering behavior because of limiting assumptions incorporated into these models. These models can only be used to predict tempering response for tempering times of less than 2 hours. On the other hand, the Creusot-Loire model [MAYN1978] can potentially be used to estimate tempered hardness values for the alloy compositions and heat treatment ranges commonly used in steel foundries.

However, none of these empirical models take into account the effect of ramp-up time to the final tempering temperature on final properties of the casting after tempering. Heat treatment qualification trials at steel foundries strongly suggest that heavy castings take a long time to reach the set-point temperature. Significant tempering will occur before castings reach the final tempering temperature.

A tempering sensitivity analysis has been conducted based on tempering models developed by Creusot Loire [MAYN1978]. The tempered hardness estimates were computed for three compositions of 8630 steel, shown in Table XXIII. Tempered hardness estimates were obtained for 8630 steels with nominal composition and for extreme compositions with the composition limits at “minimum values + 10%” from the lower composition bounds for all specified alloying elements and “maximum values - 10%” from the upper bounds for all specified alloying elements. For this tempering analysis it was assumed that the starting structure prior to tempering was 100% martensitic.

Table XXIII: 8630 steel compositions used for tempered hardness calculations using the Creusot-Loire tempering model [MAYN1978]

		%C	%Si	%Mn	%Ni	%Mo	%V	%Cr
Composition	**Min + 10%**	0.280	0.170	0.72	0.43	0.160	0	0.42
	Target	0.305	0.225	0.80	0.55	0.225	0	0.50
	Max – 10%	0.325	0.280	0.88	0.67	0.240	0	0.58

Tables XXIV and XXV show the results of the tempering sensitivity analysis for these three compositions of 8630 steel. Table XXIV shows the expected variation in tempered hardness at different tempering temperatures (tempering time held constant). For an 8630 steel of nominal composition, the variation in tempered hardness is about +/-16 HB when the tempering temperature is varied between 1100F and 1200F. The hardness variation expected due to composition variation is also shown. Rich vs. lean compositions of 8630 steel resulted in a hardness variation of about +/-7 HB at a given tempering time and temperature. Table XXV shows the variation in tempered hardness as a result of variation in tempering times. When tempering at 1100F for times ranging from 2 to 4 hours the hardness variation for a given 8630 composition was less than +/- 5 HB.

Table XXIV: Calculated quenched & tempered hardness for 8630 steels tempered for 4 hours at various temperatures using the Creusot-Loire tempering model [MAYN1978]. (Original microstructure 100% martensite)

		Tempering Temperature (F)				
		1100	**1125**	**1150**	**1175**	**1200**
Composition	**Min + 10%**	280 HB	270 HB	264 HB	255 HB	248 HB
	Nominal	284 HB	280 HB	270 HB	261 HB	252 HB
	Max – 10%	294 HB	283 HB	272 HB	264 HB	254 HB

Tempered Hardness (HB)

Table XXV: Calculated quenched & tempered hardness for 8630 steels tempered at 1100F for various hold times using the Creusot-Loire tempering model [MAYN1978]. (Original microstructure 100% martensite)

		Tempering Time (hr)				
		2	**2.5**	**3**	**3.5**	**4**
Composition	**Min + 10%**	270 HB	268 HB	266 HB	265 HB	264 HB
	Nominal	277 HB	274 HB	276 HB	271 HB	269 HB
	Max – 10%	281 HB	278 HB	271 HB	274 HB	273 HB

Tempered Hardness (HB)

Figures 36 and 37 show graphically the results of the tempering sensitivity analyses given in Tables XXIV and XXV.

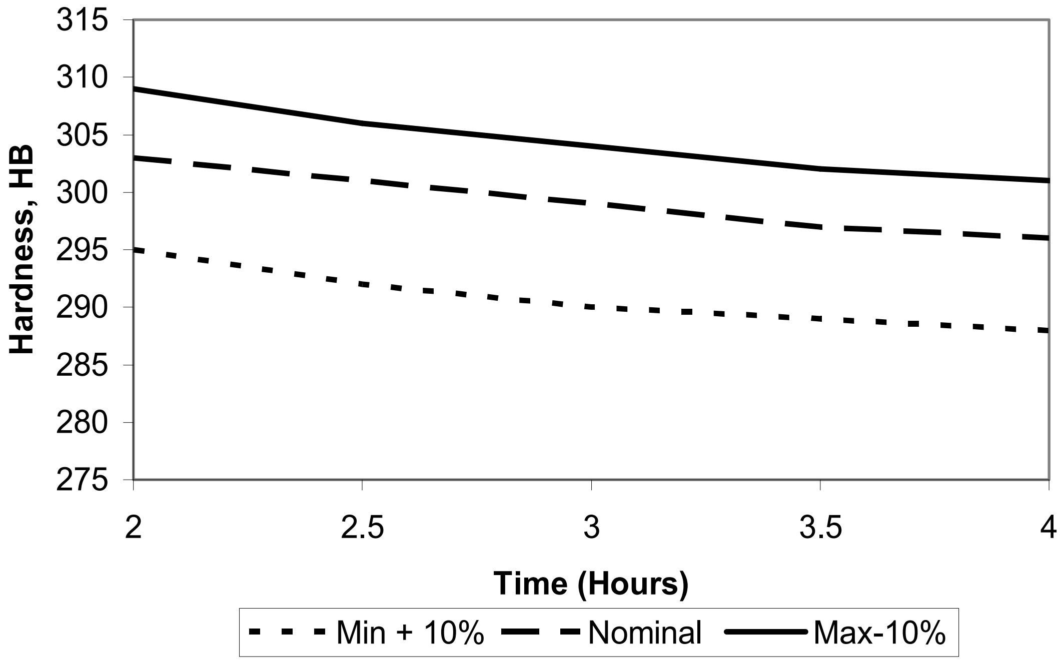


Figure 36: Calculated variation in quenched & tempered hardness as a function of tempering time at 1100F for three compositions of 8630 steel

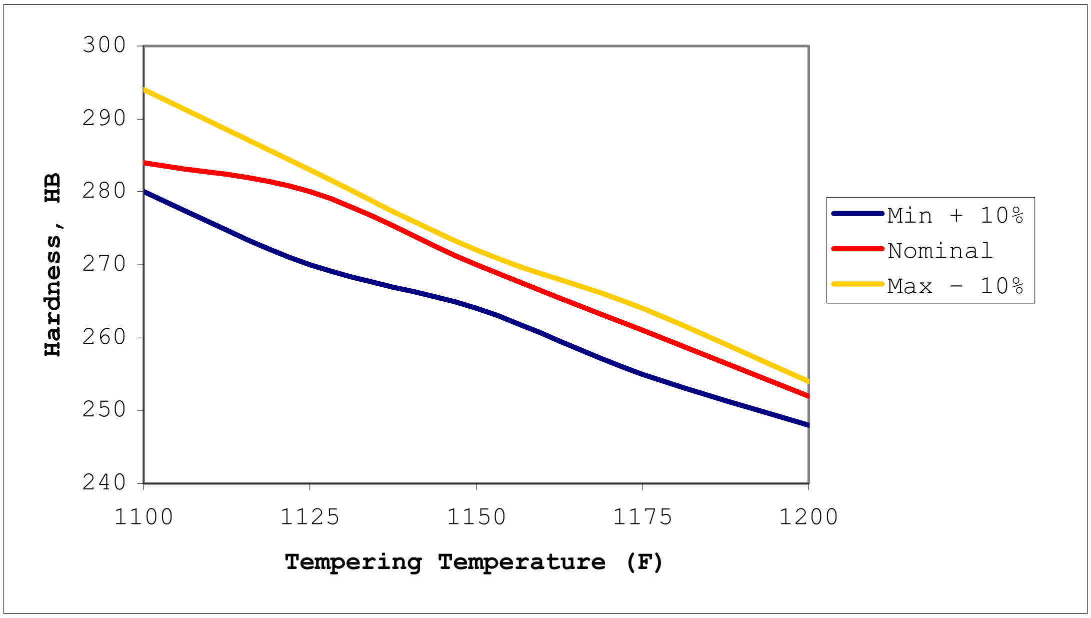


Figure 37: Calculated variation in quenched & tempered hardness as a function of tempering temperature for three compositions of 8630 steel tempered for four hours

While theoretical tempering models developed in the literature can be used for initial tempering sensitivity analysis, these models have inherent limitations. Model predictions are based on a furnace set-point temperature, and do not take into consideration tempering taking place during time/temperature ramp-up. Also, the models do not take into account casting section size effects.

2.5.3 Effects of Furnace Loading & Section Size

Additional practical challenges face heat treaters attempting to control final tempered hardness. Large heat treatment furnaces require significant ramp-up time to reach near steady-state temperatures. Large furnace loads with large section size castings within furnace loads also require significant additional time to reach near-steady-state conditions. This delayed temperature response effectively decreases the hold time at the tempering temperature. Figure 38 illustrates the delayed temperature response of heavier section size castings during tempering. The net effect of this delay is an expected increase in the final tempered hardness of castings for these furnace locations and section sizes. Therefore, to control final hardness during tempering, not only do tempering hold time and temperature have to be consistent, but consistent ramp-up is also desirable. This is particularly challenging if both room temperature and pre-heated tempering furnace starting conditions are used in a foundry.

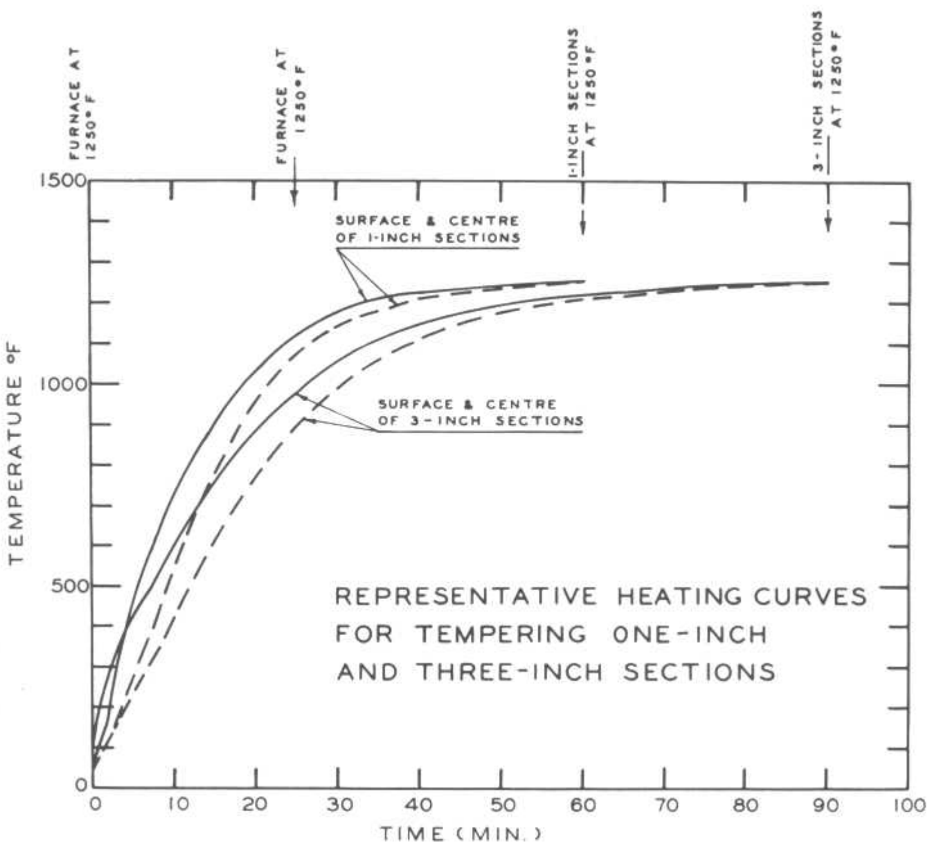


Figure 38: Tempering response for 1- and 3-inch sections of C-Mn cast steel heated to 1250F in an experimental furnace [BRIG1958]

2.5.4 Extent of Tempering Estimates

As discussed previously, a number of empirical models have been developed to estimate the effects of heat treatment variables on the final tempered hardness of wrought steels. Unfortunately, all of these models have serious short-comings, such as assuming fully martensitic starting microstructures, requiring prior experimental data, or requiring prior knowledge of the pre-tempered microstructure. Similarly, local or lot-to-lot variations in time/temperature conditions during heat treatment or variations in initial microstructure cannot be effectively modeled. However, carbon diffusion based calculations, based on localized time and temperature, can provide insight into the adequacy of heat treatment procedures and practices used by steel foundries. Carbon diffusion distance calculations can be used to estimate the extent of heat treatment using Fick's second law as described in detail in Appendix A. These "extent of heat treatment" estimates based on localized time and temperature response can be used to compare the variations in heat treatment response within foundry heat treatment furnaces.

A normalized "extent of tempering" parameter based on simple carbon diffusion distance calculations occurring during tempering for individual furnace locations during both ramp-up and hold has been determined and used to assess the tempering response observed during comprehensive HTPQ development trials at foundries. This parameter can express the combined effects of both tempering temperature and time during ramp-up and hold.

This extent of tempering parameter is much more strongly influenced by changes in tempering temperature than by changes in tempering time. Although the extent of tempering parameter is useful to express tempering variations in a tempering furnace, it cannot be directly used to predict final tempered hardness. A complete description of these "extent of heat treatment" calculations based on localized time and temperature responses during tempering (or austenitizing/solutionizing) are described in Appendix A. Extent of tempering may be calculated using Equation 1 below, represented from the extent of austenitizing section.

$$E = \frac{.3\sqrt{D_o t_{ramp,load} e^{\frac{-Q}{RT_1}}} + \sqrt{D_o t_{hold,load} e^{\frac{-Q}{RT_1}}}}{.3\sqrt{D_o t_{ramp,controller} e^{\frac{-Q}{RT_1}}} + \sqrt{D_o t_{hold,controller} e^{\frac{-Q}{RT_2}}}} \qquad (1)$$

Where:

T_1 = 95% of difference between steady state temperature room temperature
T_2 = set-point temperature
$t_{ramp,load}$ = time in seconds for load to reach T_1
$t_{hold,load}$ = time in seconds for load at or above T_1
$t_{ramp,controller}$ = time in seconds for controller to reach T_1
$t_{hold,controller}$ = time in seconds for controller at or above set-point
D_0 is the diffusion coefficient
Q is the activation energy and
T is the temperature in degrees Kelvin

2.6 Perspectives on Heat Treatment Specifications

2.6.1 Heat Treatment Specifications

A survey of heat treatment quality control specifications used by SFSA member foundries suggests that most foundries heat treat castings according to ASTM and/or MIL specifications. Other heat treatment specifications such as the SAE specifications, Norsok standards, DIN specifications and ISO specifications are less commonly used. Table XXVI summarizes the heat treatment specifications used by steel foundries. Heat treatment guidelines included in these specifications have been reviewed and compared. This includes specifications for alloy grade/ composition, furnace requirements, heat treat cycles, set-point temperatures and permissible variations, ramp up and hold times, quench media, quenchant temperature regulation, quench delay and rework of castings.

Table XXVI: List of Standards and Specifications with reference to Heat Treatment of Steel Castings

Name	Description
Heat Treatment Quality Control Specifications	
ASTM A 991/ A991M	Standard Test Method for Conducting Temperature Uniformity Surveys of Furnaces Used to Heat Treat Steel Products
AMS 2750	Pyrometry
ASTM A370-97A Sec. 10	Standard Test Methods and Definitions for Mechanical Testing of Steel Products: Procedure for use and control of heat cycle simulation
Norsok Standard M-650 [NORS1998]	Qualification of Manufacturers of Special Materials
Heat Treatment Specifications	
AMS –H- 6875A	Heat Treatment of Steel Raw Materials
AMS –H- 2759C	Heat Treatment of Steel Parts, General Requirements
Alloy Heat Treatment Specifications	
ASTM A 27	Standard Specifications for Steel Castings for General Application
ASTM A 216	Standard Specification for Steel Castings, Carbon, Suitable for Fusion Welding, for High Temperature Service
ASTM A 351	Standard Specification for Steel Castings, Austenitic, Austenitic-Ferritic (Duplex), for Pressure-Containing Parts
ASTM A 352	Standard Specification for Steel Castings, Ferritic and Martensitic, for Pressure-Containing Parts, Suitable for Low Temperature Service
ASTM A 743	Standard Specification for Castings, iron-chromium, Iron-Chromium-Nickel, Corrosion Resistant for General Application
ASTM A 744	Standard Specification for Castings, Iron-Chromium-Nickel, Corrosion Resistant for Severe Application
ASTM A 389	Standard Specification for Steel Castings, Alloy, Specially Heat-Treated, for Pressure-Containing Parts, Suitable for High Temperature Service
ASTM A 703	Standard Specification for Steel Castings, General Requirements, for Pressure-Containing Parts
ASTM A 705	Standard Specification for Age-Hardening Stainless Steel Forgings
ASTM A 487	Standard Specification for Steel Castings Suitable for Pressure Service
ASTM A 995 – 98	Standard Specification for Castings, Austenitic-Ferritic (Duplex) Stainless Steel, for Pressure-Containing Parts
AMS 2759 1C	Heat Treatment of Low-Alloy Steel Parts, Minimum Tensile Strength Below 220 ksi
AMS 2759 2C	Heat Treatment of Low-Alloy Steel Parts, Minimum Tensile Strength 220 ksi and Higher
AMS 2759 3C	Heat Treatment, Precipitation-Hardening Corrosion-Resistant and Maraging Steel Parts
AMS 2759 4B	Heat Treatment, Austenitic Corrosion Resistant Steel Parts
AMS 2759 5C	Heat Treatment, Martensitic Corrosion Resistant Steel Parts
ISO 683 - 15 to 18	Heat Treatable Steels, Alloy Steels and Free-Cutting Steels

2.6.2 Furnace Temperature Uniformity and Control

Temperature uniformity is critical to successful heat treatment. ASTM A 991 and AMS 2750 outline procedures for ensuring furnace uniformity. ASTM 991 specifies that foundries conduct temperature uniformity surveys at twelve month intervals. AMS 2750 requires quarterly temperature uniformity surveys. It stipulates the need for conducting more regular secondary surveys. It is recommended that a furnace uniformity survey is performed on a furnace with typical production weights and loads; however, furnace surveys of empty furnaces are permitted. If the operating range of the furnace is greater than 300F, then uniformity tests are recommended at the mid point temperature. ASTM A 991 also establishes working zones in the furnace. Regions of the furnace that do not conform to the furnace uniformity requirements are recommended to be avoided during heat treatment and only those zones that comply should be used for heat treatment.

It was observed from internal foundry heat treatment quality assurance documents that most foundries run furnace temperature uniformity surveys on empty furnaces. They often meet uniformity requirement targets of +/- 15 F on a tempering furnace and +/- 25F on an austenitizing furnace. However, furnace characteristics change with the type of loading in the furnace. Loaded furnaces have been observed to have variations of more than 200F from set-point temperature. AMS 2750 stipulates limits to temperature variations in furnaces: +/- 10F for temperatures below 1025F, +/- 15F for aging precipitation hardening corrosion resistant steels above 1025F and +/- 25F for all other heat treatments. Table XXVII enumerates the expected uniformity in furnaces in steel foundries. Table XXIII shows the permissible variations from set-point temperatures during actual heat treatment of steel castings.

Table XXVII: Limits on temperature uniformity in furnaces

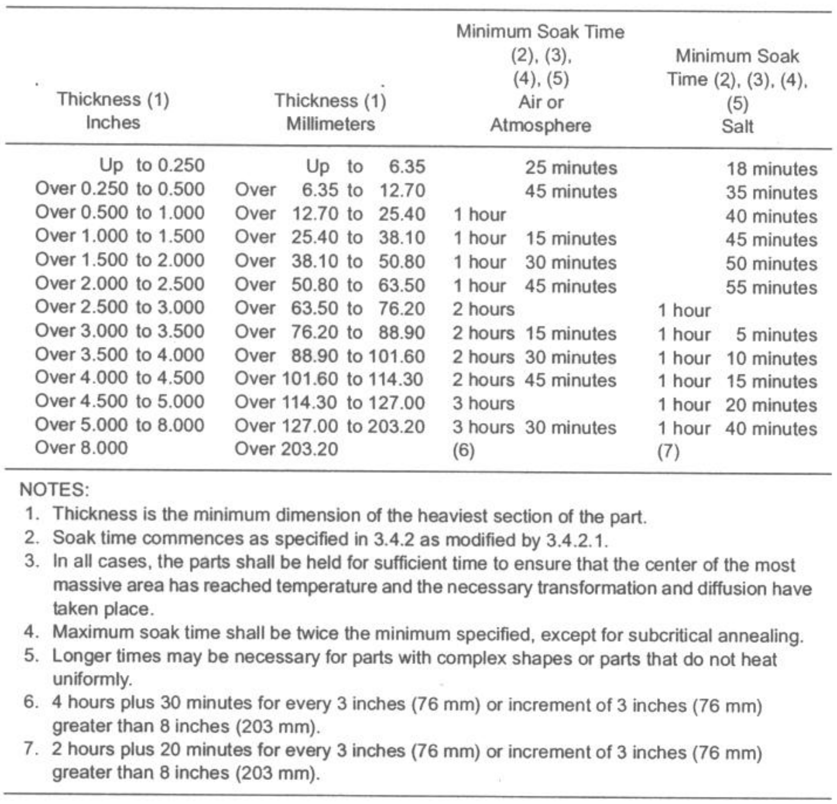
Specification	**Furnace Uniformity: Permissible Variation in Furnace Temperature from the Set-point Temperature (F)**	
	Austenitizing	**Tempering**
ASTM A 370	+/- 25	-
AMS H 2759C	+/- 10	-
AMS 2759/1C	+/- 25	+/-15
AMS 2759/2C	+/- 25	+/-15
AMS 2759/3C	+/- 25	+/-10
AMS 2759/4B	+/- 25	-
AMS 2759/5C	+/- 25	+/-15

Table XXVIII: Allowable variations from set-point temperatures

Specification	**Permissible Variation in Furnace Temperature from the Set-point Temperature (F)**
ASTM A 370	+/-25F
ASTM A 389/A 389M	100F range on N/T
ASTM A 705/A	+/-25 on Solutionizing
AMS H 6875A	+/- 25F
ISO 683 - 15 to 18	+/8F
Norsok Standard	Set-point +20F

The heat treatment process control variables that are included in the various heat treatment specifications include alloy grade, set-point temperatures, quenchant and quenchant temperature, and conditions for rework of steel castings. Heat treatment requirements in these specifications are based on alloy grade rather than their specific alloy compositions. Heat treatment set-point temperature requirements are based on alloy grades. The AMS specifications recommend soak times based on section size of the steel castings. Table XXIX shows the recommended hold times for annealing, normalizing, or austenitizing steel according to AMS 2759 1C. ISO 683 recommends a hold time of one half hour for austenitizing once the casting has reached the appropriate temperature. Table XXX outlines specification requirements for quenchant temperature control.

Table XXIX: Hold times for annealing, normalizing, and austenitizing based on section size in AMS 2759 1c



Thickness (1) Inches	Thickness (1) Millimeters	Minimum Soak Time (2), (3), (4), (5) Air or Atmosphere	Minimum Soak Time (2), (3), (4), (5) Salt
Up to 0.250	Up to 6.35	25 minutes	18 minutes
Over 0.250 to 0.500	Over 6.35 to 12.70	45 minutes	35 minutes
Over 0.500 to 1.000	Over 12.70 to 25.40	1 hour	40 minutes
Over 1.000 to 1.500	Over 25.40 to 38.10	1 hour 15 minutes	45 minutes
Over 1.500 to 2.000	Over 38.10 to 50.80	1 hour 30 minutes	50 minutes
Over 2.000 to 2.500	Over 50.80 to 63.50	1 hour 45 minutes	55 minutes
Over 2.500 to 3.000	Over 63.50 to 76.20	2 hours	1 hour
Over 3.000 to 3.500	Over 76.20 to 88.90	2 hours 15 minutes	1 hour 5 minutes
Over 3.500 to 4.000	Over 88.90 to 101.60	2 hours 30 minutes	1 hour 10 minutes
Over 4.000 to 4.500	Over 101.60 to 114.30	2 hours 45 minutes	1 hour 15 minutes
Over 4.500 to 5.000	Over 114.30 to 127.00	3 hours	1 hour 20 minutes
Over 5.000 to 8.000	Over 127.00 to 203.20	3 hours 30 minutes	1 hour 40 minutes
Over 8.000	Over 203.20	(6)	(7)

NOTES:

1. Thickness is the minimum dimension of the heaviest section of the part.
2. Soak time commences as specified in 3.4.2 as modified by 3.4.2.1.
3. In all cases, the parts shall be held for sufficient time to ensure that the center of the most massive area has reached temperature and the necessary transformation and diffusion have taken place.
4. Maximum soak time shall be twice the minimum specified, except for subcritical annealing.
5. Longer times may be necessary for parts with complex shapes or parts that do not heat uniformly.
6. 4 hours plus 30 minutes for every 3 inches (76 mm) or increment of 3 inches (76 mm) greater than 8 inches (203 mm).
7. 2 hours plus 20 minutes for every 3 inches (76 mm) or increment of 3 inches (76 mm) greater than 8 inches (203 mm).

Table XXX: Permissible operating temperature conditions for quenchants

Specification	Quenchant Temperature, F
ASTM A 370	Same or lesser than master forging
AMS –H- 6875A	60-160F
AMS –H- 2759C	60-160F
ISO 683 - 15 to 18	100F maximum

2.6.3 Existing Qualification Guidelines within Current Heat Treatment Specifications [ASTM 370-97A]

ASTM specification A370-97A Sec. 10 closely resembles a heat treatment procedure qualification methodology. Its purpose is to “ensure consistent and reproducible heat treatments of production forgings and test specimens that represent them when the practice of heat-cycle simulation is used.” Definite heat treat process values are not stipulated; they are derived from data collected through a comprehensive qualification procedure. ASTM A370-97A Sec. 10 describes a method to qualify a “master forging”, which, after the required heat treatment procedures, must meet quality requirements. A master temperature-time profile chart is then created initially from the thermocouple data from this master forging. A new master chart is required anytime the size and orientation of the forging is changed. For the actual production forgings, a set-point temperature of +/- 25F of that achieved by the master forging for an austenitizing/solutionizing cycle is stipulated. For tempering, the set-point temperature on the production forging should not fall below the set-point of master forging. However, no upper limit on tempering temperature is specified. ASTM A370-97A Sec. 10 specifies that the initial temperature of the quenchant should not be lower than the temperature at which the master forging was heat treated. The agitation in the quench tank is expected to be the same as for the master forging. Documenting of quench delay is required. Any delay greater than that for the master forging requires that the production forgings be brought back to the intended set-point temperature before quenching. Production forgings are required to be oriented similarly to the master forging in both the furnace and the quench tank. In the event of failure of a test specimen, the test specimen is to be re-heat treated with all production forgings.

The ASTM A370-97A Sec. 10 specification is flexible in some ways, in that it does not specify set-point temperatures or heat treat cycle times. The heat treater is required to successfully heat treat a master forging and continue the same heat treatment practices for the production forgings. Though this flexibility may seem attractive to foundries, the specification does not adequately constrain certain heat treatment variables and too rigidly restricts others. Upper limits on tempering temperature are not specified within the document. Part mixes and the effects of loading while documenting the temperature behavior for the master forging are not taken into account. Consequently, any variations in furnace loading(or furnace conditions) would hinder the ability of the heat treater to adhere to the specified limits on temperature, or would necessitate the use of longer/shorter heat treatment hold and ramp up times. ASTM A370-97A Sec. 10 requires the heat treater to monitor the quench tank agitation, but surveys from foundries indicate that quench tank agitation is not a variable that foundries constantly monitor. Foundries are also required to monitor cooling rates on the forgings.

A comparative evaluation of specifications with heat treatment requirements shows that AMS heat treatment specifications are more detailed and rigid compared to the ASTM and ISO heat treatment specifications. Furnace temperature uniformity requirements are specified by both ASTM 370 and AMS 2759. However, the furnace uniformity specified by the ASTM specification is with respect to a successful qualification temperature. On the other hand, the AMS specification mandates furnace uniformity based on the set-point temperature. Results from heat treatment surveys of steel foundries show variations up to 120F in heat treating furnaces, well outside of the AMS 2759 specification guideline. The AMS specifications stipulate the cooling rates for alloy steels whereas ASTM A370-97A Sec. 10 bases it on the master forging, thereby accommodating foundry to foundry variability in the specifications. AMS 2759 requires foundries to do furnace uniformity surveys, equipment recalibration, quench rate control tests etc., on a quarterly basis. However, the rigidity of this specification makes it difficult for and heat treater to completely comply with AMS 2759 in practice.

Almost all heat treatment specifications qualify a particular grade of steel. They do not take into account the variations in properties that could be attained as a result of changes in composition within a grade of steel. Furnace temperature uniformity qualification is done once a year at foundries following ASTM 991 A which is perhaps not soon enough to detect changes in furnace uniformity conditions.

3.0 Summary

A heat treatment procedure qualification schema has been developed based on heat treatment science and laboratory and foundry heat treatment studies. This study has demonstrated the benefits of using heat treatment procedure qualification methodologies in steel foundries and has identified action that can be taken by foundries to improve their individual heat treatment practices.

Furnace load time-temperature profiles in steel foundries exhibit significant differences depending on heat treatment equipment, furnace loading practice, and furnace maintenance. The time-temperature profiles of heat treatment furnace control thermocouples can be very different from the time-temperature profiles observed at the center of casting loads in the furnace. Improvements in heat treatment practice are possible based on the direct measurement of load-based heat treatment time and temperature cycles, which are in many cases quite different than the heat treatment time and temperature cycles indicated by the furnace controller. Ultimately, it is the time and temperature response of the heat treated castings rather than the time and temperature of the furnace that controls treated properties. The “extent of heat treatment” measurement developed in this study allows foundries to directly assess the influence of heat treatment time and temperature on heat treatment performance both during temperature ramp-up and hold cycles.

Typical austenitizing heat treatment temperatures used for steel castings are well above the minimum required austenitizing temperature as well as being significantly above the recommended austenitizing temperatures for equivalent wrought grades. Excessively long austenitizing hold times are also typically used in steel foundries. These hold times at the austenitizing temperature are well beyond the minimum hold times for complete transformation of the as-cast microstructure to austenite. For carbon and low alloy steels, once the austenitization temperature is reached, transformation of the microstructure to austenite happens very quickly. Generally speaking, a relatively small increase in austenitizing temperature will have a far greater effect on extent of heat treatment than a longer soak time. This precludes the need for long soaking times.

When austenitizing at temperatures above 1650F, austenitizing times of much less than one hour per inch of thickness are required. Bates studied 5 inch thick sections placed into a furnace at 1650-1700F and found that the temperature of the center of the castings lagged behind that of the surface by only about 15 minutes. These heat treatment data clearly show that the long heat treatment hold cycles commonly used by steel foundries can be traced to the delays in getting the center of furnace loads up to the desired austenitizing temperature in heavily loaded furnaces.

Furnace loading is a key heat treatment parameter influencing the time-temperature profiles of furnace loads during heat-up to the austenitizing temperature. Loading must consider the weight of the furnace load, as well as the load density. This suggests that control strategies based on the temperature of the surface of the casting load rather than on the furnace temperature itself could be expected to shorten the time necessary to fully austenitize castings. However, in laboratory trials, the use of these advanced control strategies to shorted austenitizing time resulted in only marginal decreases in the required heat treatment times.

At the solutionizing temperatures commonly used by steel foundries, re-solution of carbidic phases can be expected to take place very quickly. This study strongly suggests that, as for carbon and low alloy steels, the critical heat treatment practice issue is to get the furnace load to the desired temperature. Excess furnace hold times are not necessary to resolutionize carbides, except to guarantee that all portions of the furnace load reach the desired solutionizing temperature.

Quenching equipment affects the ability of the heat treater to cool the casting uniformly and quickly. The effective quench severity experienced by a casting is influenced by many factors. The tank volume compared to the load size, as well as quenchant temperature and velocity are critical.

For carbon and low alloy steels the critical cooling rate to avoid the ‘pearlite nose’ of the austenite transformation diagram depends on the hardenability of the alloy being quenched. Casting section size is an important consideration in quenching. As the casting section size increases, the alloy content of the steel and/or the quench severity must be increased to insure adequate quenching cooling rates at the center of the casting. Agitation can effectively increase quench severity for most production heat treating by interrupting the vapor blanket that forms in the first stages of cooling. Large, complex casting shapes and large quench tank loads can stretch the limit of quench tanks to provide adequate quench severity during quenching.

The effective severity of a quench can be expected to vary significantly from the outside of a quench tank load to the center of a densely-packed quench tank load, independent of casting section size. Even when the combination of casting section size, hardenability and overall quench tank quench severity are sufficient to ensure adequate quenching of a given casting section, adequate quenching of casting sections in the center of quench tank loads is not guaranteed. Therefore, it is important to conduct critical HTPQ tests from castings located in the center of casting loads.

Tempering success is dependent on both tempering time and temperature. As such, furnace temperature uniformity and control of furnace loading during tempering is critical to obtain the desired mechanical properties. The ramp-up time in the furnace prior to the establishment of steady state heat treatment conditions contributes to the extent of heat treatment. This influence of ramp-up to temperature during tempering can be effectively quantified with extent of heat treatment concepts.

A wide range of acceptable tempering temperatures and times can be selected to achieve final properties for a given cast steel alloy. Similarly, a given cast steel composition can often be heat treated to produce different grades of material simply by adjusting the tempering time and temperature. In practice, tempering temperature has a much more dominant effect on tempered hardness than tempering time. Success during tempering is determined by successful targeting of the final tempered hardness. It is therefore not necessary to restrict tempering practices with unnecessary HTPQ guidelines.

Researchers have developed reasonable, but rarely used, models that can be used to predict the tempered hardness of wrought steels as a function of composition, initial microstructure, tempering time and tempering temperature. However, foundry and laboratory heat treatment trials have shown that these wrought steel tempering models from the literature cannot be used to predict cast steel tempered hardness values. However, these models have been successfully used in sensitivity analysis to show the critical parameters affecting tempered hardness variations.

Large tempering furnace loads of large section size castings can be expected to require significant additional time to reach near-steady-state conditions. This delayed temperature response effectively increases the tempering ramp-up time and correspondingly decreases the hold time at the tempering temperature resulting in wide variations in tempered hardness values unless the extent of heat treatment during tempering is strictly controlled.

Hardenability concepts can be effectively used to predict the heat treatment response of carbon and low alloy steels. These concepts have been combined with quench severity data to provide a wide HTPQ pre-qualification window that precludes excessive HTPQ testing and cost. Successful qualification of a given alloy composition and section size can be used to define an effective HTPQ quench severity. Based on this HTPQ quench severity determination from a successful HTPQ test, other combinations of alloy composition and section sizes requiring lesser quench severities can be considered to be HTPQ pre-qualified. Using this strategy, a foundry can effectively use a single aggressive qualification test to pre-qualify most of the common carbon and low alloy heat treatments performed in their facility.

Because of the direct relationship between martensite hardness and alloy carbon content, it is possible to also use quenched hardness values as an indication of heat treatment qualification success for carbon and low alloy steels. This method of HTPQ requires no heat treatment time and temperature documentation. Rather, it requires measurement of the quenched hardness as a demonstration of heat treatment success for all castings subjected to heat treatment.

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Appendix A: Extent of Heat Treatment

During austenitizing, heat treatments performed at varying times and temperatures may be compared to each other by evaluating the "extent of heat treatment" based on diffusion concepts. The extent of heat treatment can be approximated by using classical carbon diffusion distance calculations. Carbon diffusion distance (Z) during heat treatment can be calculated using Fick's second law, which is mathematically stated as

$$\frac{\delta\left(D\frac{\delta C}{\delta Z}\right)}{\delta Z} = \frac{\delta C}{Dt} \qquad \text{(A1)}$$

Where:

D is the diffusion coefficient, cm^2/s
C is the volume concentration of a component, g/cm^3 or $atoms/cm^3$
Z is the diffusion distance
t is the time in seconds.

By applying suitable Laplace transformations for given boundary conditions, the solution to Equation A1 can be written in terms of an error function as shown.

$$C(Z,t) = \frac{C_o}{2\left[\frac{1-erf(Z)}{2\sqrt{Dt}}\right]} \qquad \text{(A2)}$$

Where:

"erf" is an error function
t = time at temperature

Using tabulated error function values, diffusion distances can be readily determined. However, this equation can be further simplified for the case of isothermal diffusion. During isothermal diffusion the diffusion distance can be approximated by:

$$Z = K\sqrt{Dt} \qquad \text{(A3)}$$

Where:

Z = diffusion distance
D = diffusion coefficient
t = time at temperature
K = constant of proportionality

While not an exact solution to Fick's second law, this solution represents a reasonable first order approximation.

The diffusion coefficient, D, in Equation A3 varies exponentially with temperature according to the expression:

$$D = D_o e^{\frac{-Q}{RT}} \qquad \text{(A4)}$$

Where:

D_0 is the diffusion coefficient
Q is the activation energy and
T is the temperature in degrees Kelvin

Any determination of the extent of heat treatment must include the amount of diffusion that takes place during both ramp-up and holding at the furnace set-point temperature. By considering diffusion occurring during ramp-up and hold, the total carbon diffusion distance (extent of heat treatment) may be determined. The total diffusion distance during a conventional ramp-up and hold heat treatment cycle can be expressed by the following equation:

$$Z = \int_{0}^{t} \left(t_1 \int_0^T D_o e^{\frac{-Q}{RT}} \right)^{\frac{1}{2}} dT dt_1 + \sqrt{Dt_2} \qquad \text{(A5)}$$

Where:

Z=diffusion distance
t_1 = Time to temperature (Heating time)
t_2 = Time at temperature (Holding time)

Iron at room temperature exists in as a BCC structure, but transforms to FCC as the temperature increases. To account for this, appropriate D_0 and Q values are needed to calculate diffusion distances in the lower temperature BCC and higher temperature FCC temperature regions during heat treatment. However, carbon diffusion distances in the BCC temperature regions are very low. Therefore, slight errors associated with using FCC values for D_0 and Q for the entire heating range are negligible for common austenitizing heat treatments. Diffusion distances upon which extent of heat treatment estimates are made can be computed numerically using the diffusion coefficient values from the literature, Table CI.

Table CI: Parameters for calculation of diffusion distances

Alloy Group	**Process**	**Lattice**	**Valid Temp. (ºF)**	***D_O (cm^2/sec)**	****Q (cal/mole)**
Low & Medium Alloy Steels	Tempering	BCC	<1333	0.02	24100
Low & Medium Alloy Steels	Austenitizing	FCC	>1333	0.12	32000
High Alloy Steels	Solutionizing	FCC	>0	0.32	37800

*Diffusion coefficient at 298 K
**Activation Energy

This method to determine the extent of heat treatment during heat treatment ramp-up and hold is cumbersome. However simpler extent of heat treatment calculation methods have been developed based on laboratory studies conducted at Penn State. Using thermocouple-collected data during comprehensive HTPQ development trials at steel foundries and in the Penn State laboratory, various methods to delineate ramp-up time from hold times were investigated. Extent of diffusion calculations (Equation A5) were first made with cutoffs between ramp-up and hold time based on the times at which the thermocouples reached 90%, 95% and 99% of the steady state set-point temperature. From these calculations, empirical values of the ramp-up contribution to overall extent of heat treatment, α, were determined. The total carbon diffusion distance during heat treatment can then be expressed by the following equation:

$$Z_{total} = \alpha Z_{ramp} + Z_{hold} \tag{A6}$$

Where:

Z_{total} = total diffusion distance of a particular temperature profile
Z_{ramp} = diffusion distance calculation based on the total ramp-up time at the steady state furnace temperature
Z_{hold}=diffusion distance during hold
α= empirically determined ramp-up diffusion distance correction factor

Alpha, α, was then computed for temperature profiles at 99, 95 and 90% of set-point temperatures for tempering response during HTPQ development trials. The value of α with minimum variance at a particular temperature level was accepted as the best criteria of delineation for ramp-up and hold time estimates. These calculated α values were then fit to a probability distribution to determine the most reliable way to estimate the end of ramp-up time and hold time from load thermocouple responses. From these calculations, a hold time criteria based on a value of 95% of the set-point temperature was established as the best value to repeatably distinguish between ramp-up and hold periods. This 95% value is determined from the difference between the furnace temperature and room temperature.

$$T_c = 95\%(T_{furnacesetpoint} - T_{roomtemp}) + T_{roomtemp} \tag{A7}$$

Where:

T_C = criteria temperature for determining the ramp-up and hold time for HTPQ

Alpha values were then estimated based on this 95% of set-point ramp-up criterion for a large number of laboratory heat treatments. A best-fit analysis resulted in an α value of 0.3. Heat treaters can effectively use this alpha value to estimate diffusion distances during ramp-up for the purposes of HTPQ pre-qualification.

For example, a tempering cycle with a 100 minute ramp-up followed by a 100 minute hold promotes approximately the same amount of tempering as a 200 minute ramp-up to temperature followed by a 70 minute hold. It should be noted that the extent of heat treatment occurring during ramp-up can be expected to be different from foundry to foundry depending on the dynamics of their heat treatment furnaces that could be expected to change the appropriate value of α somewhat. An example calculation may be found at the end of this appendix.

Once the ramp-up time and hold time have been determined, the total extent of heat treatment (E) may be estimated. This E parameter normalizes the heat treatment experienced by the load during ramp-up and hold compared to the heat treatment expected using the furnace controller during ramp-up and hold. The extent of heat treatment parameter, E, is calculated by dividing the total carbon diffusion distance for the furnace load by the carbon diffusion distance experienced by the furnace controller thermocouple. The extent of heat treatment (E) can be approximated for α = 0.3 using the following equations:

$$E = \frac{Z_{total,load}}{Z_{total,controller}} \tag{A8}$$

$$E = \frac{.3\sqrt{D_o t_{ramp,load} e^{\frac{-Q}{RT_1}}} + \sqrt{D_o t_{hold,load} e^{\frac{-Q}{RT_1}}}}{.3\sqrt{D_o t_{ramp,controller} e^{\frac{-Q}{RT_1}}} + \sqrt{D_o t_{hold,controller} e^{\frac{-Q}{RT_2}}}} \tag{A9}$$

Where:

T_1 = 95% of difference between steady state temperature room temperature
T_2 = set-point temperature
$t_{ramp,load}$ = time in seconds for load to reach T_1
$t_{hold,load}$ = time in seconds for load at or above T_1
$t_{ramp,controller}$ = time in seconds for controller to reach T_1
$t_{hold,controller}$ = time in seconds for controller at or above set-point

EXAMPLE CALCULATION
Parameters for the calculation of diffusion distances

For Tempering of a 1040 steel (BCC crystal lattice)

D_O, the diffusion coefficient at 298K = 0.02 cm^2/sec
Q, the activation energy = 24100 cal/mole

The diffusion distance for tempering of 1040 steel at 1100 °F (593 °C), no ramp up, 1 hour hold is given by:

$$Z = \int_0^t \left(t_1 \int_0^T D_o e^{\frac{-Q}{RT}} \right)^{\frac{1}{2}} dT dt_1 + \sqrt{Dt_2}$$

$$= \int_0^0 \left(0 \int_0^{866} 0.02 e^{\frac{-24100}{(1.987 \cdot 866)}} \right)^{\frac{1}{2}} dT dt_1 + \left(0.02 e^{\frac{-24100}{(1.987 \cdot 866)}} \cdot 3600 \right)^{\frac{1}{2}}$$

$$= .008 cm$$

Appendix B

Standard Practice for Qualification of Heat Treatment Procedures for Carbon and Low Alloy Steel Castings

April 30, 2004 DRAFT

1.Scope

1.1 This practice establishes the qualification of procedures for the heat treatment of carbon and low alloy steel castings.

1.2 Each manufacturer or contractor is responsible for the heat treatment performed by the organization and shall conduct the testing required to qualify a heat treatment procedure. Castings successfully heat treated within the scope of these procedures may use the 'HTPQ' (heat treatment procedure qualified) designation.

1.3 Each manufacturer or contractor shall maintain a record of all heat treatment qualification tests.

1.4 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents: therefore, each system must be used independently of the other. Combining values from the two systems may result in non-conformance with this practice.

2. Referenced Documents

ASTM A985
ASTM A957
ASTM A781
ASTM A703
ASTM A370
ASTM E8
ASTM E10

3. Terminology

3.1 Heat treatment cycle: The sequence and type of thermal events, which may be used to produce particular mechanical properties.

3.2 Heat treatment events: Heat treatment events include the following:

3.2.1 Austenitize – heating an alloy above the transformation temperature to form austenite.

3.2.2. Anneal - heating to a temperature high enough to produce a fully austenitic structure followed by slow cooling to produce a structure that does not contain martensite

3.2.3 Normalize - heating to a temperature high enough to produce a fully austenitic structure followed by cooling in air to produce a structure that may contain martensite.

3.2.4 Homogenize –a pre-heat treatment heating to a temperature high enough and holding the alloy at the temperature for a sufficient amount of time to reduce chemical segregation. It is followed by austenitizing, annealing, or normalizing.

3.2.5 Quench - rapid cooling from the austenitizing temperature. The part may be cooled in a liquid or rapidly moving air or gas.

3.2.6 Temper - heating to a temperature below the austenite transformation temperature range to modify mechanical properties.

3.2.7 Furnace Load Density - Total weight of the casting loaded into the heat treatment furnace divided by the working volume of the heat treatment furnace.

3.2.8 Local Load Density – Weight of a grouping of castings consolidated in a local region of the heat treatment furnace divided by the volume of the consolidated group of castings.

4 Heat Treatment Procedure Qualification

4.1 Test Blocks: Heat Treatment procedure qualification test castings may be selected from ASTM A703, A781, A957 or A985, alternative test block designs required by other material standards, or separately cast test plates. The section size of the test block shall be the maximum section thickness qualified. The chemical composition of the heat from which the test blocks are poured shall be recorded.

4.2 Preparation of test specimens: Mechanical test coupons shall be machined from the test block sections after undergoing the specified thermal cycle.

4.3 Types of Tests

Tension test
Charpy impact test
Hardness test

4.3.1 Tension Test

4.3.1.1 One tension test shall be performed and conform to the tensile requirements required in the material specification, test bars shall be prepared from the test block according to ASTM E8.

4.3.1.2 If the specimen shows defective machining or develops flaws, it may be discarded and another substituted from the same heat treatment procedure qualification test casting. In the event that the mechanical performance of specimens fails to meet the acceptance standard, two additional test specimens may be taken from the same block and retested. Should either set of test fail to meet the requirements, then the procedure is not qualified.

4.3.2 Charpy Impact Test: Testing shall be performed according to ASTM A370.

4.3.3 Hardness Test: Quenched hardness tests on the surface of the block shall be recorded after quenching and before any subsequent thermal treatment according to ASTM A370

5. Heat Treatment Procedure Qualification (HTPQ) documentation

5.1 Material: The alloy grade and chemical composition of the steel for heat treatment procedure qualification shall be recorded along with the section size of the test block. The hardenability (ideal critical diameter -- D_I) shall be calculated from the composition of the heat test block according to Table II and Table III.

5.2 Furnace loading: Heat treatment procedure qualification trials must be conducted on loaded furnaces with test plates located both in the center and at the edge of the load for each stage of the heat treatment cycle. The load weight, the furnace load density, and the local load density shall be recorded.

5.3 Qualification Procedures: Heat treatment procedure qualification testing is to be performed using one of the following HTPQ procedures:

Procedure A – Single Furnace HTPQ Method
Procedure B – Multiple Furnace HTPQ Method
Procedure C – Quenched Hardness HTPQ Method

A5.4 Procedure A – Single Furnace HTPQ: Procedure A is used to qualify a particular heat treatment furnace or heat treatment furnace combination for multistage heat treatments. It does not require the instrumentation of actual heat treatment loads during heat treatment qualification procedures or during subsequent qualified heat treatments.

A5.4.1 Qualification Temperature: The reported qualification temperature shall be recorded as the furnace thermal treatment temperature.

A5.4.2 Qualification Time: The reported qualification time shall be reported as the total time at the furnace thermal treatment temperature.

A5.4.3 Transfer time: The transfer time for removal from the furnace to the onset of cooling/quenching shall be recorded for quenching only. Transfer time during quenching is measured from the time the furnace door is opened until the furnace load is completely immersed in the quenchant.

A5.4.4 Quenching: The quenchant temperature shall be measured immediately prior to and immediately after the load has been quenched. The immersion time of the HTPQ load in the quench tank shall be recorded. Quenchant velocity shall be measured immediately prior to testing at a quench tank location without any casting load in the quench tank.

A5.4.5 Cooling: If forced air or gas cooling instead of quenching is employed, the air or gas velocity should be measured and recorded.

A5.4.6 Final Tempering: Test blocks must be located both at the center and at the edge of the furnace load or basket during tempering. Furnace loading during tempering may not exceed the furnace loading used to qualify the heat treatment procedure. The reported tempering temperature shall be recorded as the furnace set-point temperature. The reported tempering ramp-up time to the furnace set-point temperature and the hold time at the set-point tempering temperature shall be recorded. The method of cooling from the tempering temperature shall be recorded. The final tempered hardness of the test block surface shall be recorded.

A6. Re-qualification of a heat treatment procedure: A heat treatment procedure must be re-qualified when any of the changes listed below are made. Changes to heat treatment procedures other than those listed, may be made without re-qualification. Furnace controllers must be calibrated every six months to retain HTPQ certification.

A6.1 A different heat treatment furnace to the one already qualified is used.

A6.2 A change in furnace design or conditions involving the method of firing, furnace insulation, shape changes to the furnace working volume.

A6.3 A furnace load density or local load density greater than 110% of the load densities used during qualification.

A6.4 A decrease in the furnace thermal treatment temperatures or a decrease in the furnace thermal treatment hold time.

A6.5 A change in quenchant, quench tank design or agitation system design that decreases quench severity.

A6.6 An increase in the quench delay time by more than 25%. An increase in the forced air or gas cooling delay time during normalizing by more than 50%.

A6.7 An increase in the final quench tank temperatures above 110 F. If the HTPQ final quench tank temperature was greater than 110 F, then the final quench tank temperature during qualification is the maximum acceptable quench tank temperature.

A6.8 A change in alloy composition and/or section size that results in a decreased effective quench severity as determined in Table IV or Table V.

B5.4 Procedure B – Multiple Furnace HTPQ: Procedure B is used to qualify heat treatments based on temperature measurement from furnace load thermocouples. It requires the temperature instrumentation of actual heat treatment furnace loads during heat treatment procedure qualification testing.

B5.4.1 Qualification Temperature: The reported thermal treatment temperature shall be the temperature recorded by a thermocouple placed at the center of the casting load (load thermocouple) during qualification testing. The reported thermal treatment time shall be reported as the hold time (time at temperature) of the load thermocouple. The corresponding furnace thermal treatment temperature and time at temperature shall also be recorded.

B5.4.2 Transfer time: The transfer time for removal from the furnace to the onset of cooling/quenching shall be recorded for quenching only. Transfer time during quenching is measured from the time the furnace door is opened until the furnace load is completely immersed in the quenchant.

B5.4.3 Quenching: The quench tank shall permit complete immersion of the material and provide for adequate circulation of the quenchant. The quenchant temperature shall be measured immediately prior to and immediately after the load has been quenched. The immersion time of the load in the quench tank shall be recorded. Quenchant velocity shall be measured prior to testing at a fixed quench tank location without any casting load in the quench tank.

B5.4.4 Cooling: If forced air or gas cooling instead of quenching is employed, the air or gas velocity should be measured and recorded.

B5.4.5 Final Tempering: Test blocks must be located both at the center and at the edge of the furnace load or basket during tempering. Furnace loading during tempering may not exceed the furnace loading used to qualify the heat treatment procedure. The reported tempering temperature shall be recorded as the furnace set-point temperature. The reported tempering ramp-up time to the furnace set-point temperature and the hold time at the set-point tempering temperature shall be recorded. The method of cooling from the tempering temperature shall be recorded. The final tempered hardness of the test block surface shall be recorded.

B6. Re-qualification of a heat treatment procedure: A heat treatment procedure must be re-qualified when any of the changes listed below are made. Changes to heat treatment procedures other than those listed may be made without re-qualification. Furnace controllers must be calibrated every six months to retain HTPQ certification.

B6.1 A furnace load density or local load density greater than 110% of the load densities used during qualification

B6.2 An increase in casting section size beyond the qualification test block section size.

B6.2 A decrease in the thermal treatment qualifying temperature or a decrease in the qualifying hold time as indicated by load thermocouples or by the corresponding furnace temperature and time at temperature.

B6.3 A change in quenchant, quench tank design or agitation system design that decreases quench severity.

B6.4 An increase in the quench delay time by more than 25%. An increase in the furnace air or gas cooling delay time during normalizing by more than 50%.

B6.5 An increase in the final quench tank temperatures above 110 F. If the HTPQ final quench tank temperature was greater than 110 F, then the final quench tank temperature during qualification is the maximum acceptable quench tank temperature.

B6.6 A change in alloy composition and/or section size that results in a decreased effective quench severity as determined in Table IV.

B6.7 The use of other heat treatment furnaces, changes in furnace treatment temperatures or time at temperature that reduce the load thermal treatment temperature or time at temperature used for qualification.

B6.8 When the furnace thermal treatment temperature and furnace thermal treatment time at temperature for any furnace used for thermal treatment cannot be linked to the expected load thermocouple temperature and load thermocouple time at temperature.

C5.4 Procedure C – Quenched Hardness HTPQ: Procedure C qualifies a quench and temper heat treatment based on the measurement of the surface hardness of castings after austenitizing and quenching. Furnace load instrumentation may be used.

C5.4.1 Qualification Temperature: The qualification temperature during austenitizing shall be recorded as a furnace thermal treatment temperature to qualify a single furnace or as the load thermal treatment temperature.

C5.4.2 Qualification Time: The furnace thermal treatment time shall be recorded as the total time at the furnace thermal treatment temperature or the total time at the load thermal treatment temperature.

C5.4.3 Transfer time: The transfer time for removal from the furnace to the onset of cooling/quenching shall be recorded for quenching only. Transfer time during quenching is measured from the time the furnace door is opened until the furnace load is completely immersed in the quenchant.

C5.4.4 Quenching: The quenchant temperature shall be measured immediately prior to and immediately after the load has been quenched. The immersion time of the HTPQ load in the quench tank shall be recorded. Quenchant velocity shall be measured immediately prior to testing at a quench tank location without any casting load in the quench tank.

C5.4.5 Final Tempering: Test blocks must be located both at the center and at the edge of the furnace load or basket during tempering. Furnace loading during tempering may not exceed the furnace loading used to qualify the heat treatment procedure. The reported tempering temperature shall be recorded as the furnace set-point temperature. The reported tempering ramp-up time to the furnace set-point temperature and the hold time at the set-point tempering temperature shall be recorded. The method of cooling from the tempering temperature shall be recorded. The final tempered hardness of the test block surface shall be recorded.

C5.4.6 The Brinell (HBW) hardness of the surface of all quenched test blocks shall be measured according to ASTM E10. Demonstration of qualification by quenched hardness values is required for all subsequent casting loads using qualification procedure C. Successful qualification of a load is achieved when the qualified test specimen hardness is greater than or equal to the hardness value indicated in Table I based on the carbon content of the alloy being quenched.

Table I: Minimum quenched hardness values based on alloy carbon content.

%C	BHN
0.10	301
0.15	336
0.20	381
0.25	422
0.30	456
0.35	488
0.40	521
0.45	557
0.50	597
0.55	637
0.60	669
0.65	687
0.70	688
0.75	688
0.80	688

C6. Re-qualification of thermal treatment procedures are not necessary for Procedure C

7. Ideal Critical Diameter Calculation and Quench Severity Estimation

7.1 Ideal critical diameter, $D_{I,}$ can be calculated from Table II and Table III for carbon and low alloy steels. The appropriate numbers in Table II corresponding to the percentage of each alloying element present are summed. The resulting sum is used to determine the value of D_I for the overall alloy in Table III.

Table II: Alloy D_I Factors used for overall D_I calculation [1]

% Element	Alloy D_I Factors C	Mn	Si	Cr	Ni	Cu	Mo
0.20	0.1458	0.2227	0.0569	0.1556	0.0306	0.0306	0.2041
0.25	0.1929	0.2636	0.0700	0.1875	0.0378	0.0378	0.2430
0.30	0.2317	0.3010	0.0828	0.2170	0.0453	0.0453	0.2788
0.35	0.2658	0.3306	0.0952	0.2445	0.0523	0.0523	0.3118
0.40	0.2967	0.3677	0.1072	0.2705	0.0592	0.0592	0.3424
0.45	0.3222	0.3976	0.1189	0.2949	0.0663	0.0663	0.3711
0.50	0.3444	0.4255	0.1303	0.3181	0.0730	0.0730	0.3979
0.55	0.3614	0.4518	0.1415	0.3403	0.0795	0.0795	
0.60	0.3838	0.4767	0.1523	0.3610	0.0860	0.0860	
0.65		0.5001	0.1629	0.3811	0.0924	0.0924	
0.70		0.5226	0.1732	0.4000	0.0986	0.0986	
0.75		0.5437	0.1833	0.4185	0.1052	0.1052	
0.80		0.5640	0.1931	0.4358	0.1109	0.1109	
0.85		0.5831	0.2028	0.4528	0.1169	0.1169	
0.90		0.6017	0.2122	0.4689	0.1229	0.1229	
0.95		0.6192	0.2214	0.4847	0.1284	0.1284	
1.00		0.6368	0.2305	0.4997	0.1339	0.1339	
1.05		0.6531	0.2393	0.5142	0.1399	0.1399	
1.10		0.6688	0.2480	0.5284	0.1461	0.1461	
1.15		0.6840	0.2565	0.5422	0.1517	0.1517	
1.20		0.6986	0.2648	0.5553	0.1569	0.1569	
1.25		0.7199	0.2730	0.5683	0.1626	0.1626	
1.30		0.7401	0.2810	0.5807	0.1679	0.1679	
1.35		0.7593	0.2889	0.5930	0.1735	0.1735	
1.40		0.7779	0.2967	0.6047	0.1790	0.1790	
1.45		0.7961	0.3043	0.6163	0.1847	0.1847	
1.50		0.8137	0.3118	0.6274	0.1901	0.1901	
1.55		0.8304	0.3191	0.6384	0.1967	0.1967	
1.60		0.8464	0.3263	0.6490	0.2030	0.2030	
1.65		0.8625		0.6594	0.2093	0.2093	
1.70		0.8777		0.6695	0.2151	0.2151	
1.75		0.8923		0.6795	0.2217	0.2217	
1.80		0.9064		0.6891	0.2279	0.2279	
1.85		0.9199		0.6987	0.2335	0.2335	
1.90		0.9303		0.7079	0.2430	0.2430	
1.95		0.9440		0.7171	0.2453	0.2453	
2.00		0.9584		0.7259	0.2499	0.2499	
2.05					0.2560	0.2560	
2.10					0.2620	0.2620	
2.15					0.2686	0.2686	
2.20					0.2751	0.2751	
2.25					0.2817	0.2817	
2.30					0.2880	0.2880	
2.35					0.2956	0.2956	
2.40					0.3030	0.3030	
2.45					0.3107	0.3107	
2.50					0.3181	0.3181	

[1] Total alloy D_I is obtained by adding together the individual Alloy D_I factors

Table III: Total Alloy D_I Factor based on the sum of individual alloy factors from Table 1.

Sum of Individual Alloy D_I Factors	Overall D_I	Sum of Individual Alloy D_I Factors	Overall D_I	Sum of Individual Alloy D_I Factors	Overall D_I	Sum of Individual Alloy D_I Factors	Overall D_I
1.00	1.00	1.22	1.66	1.44	2.75	1.66	4.57
1.01	1.02	1.23	1.70	1.45	2.82	1.67	4.68
1.02	1.05	1.24	1.74	1.46	2.88	1.68	4.79
1.03	1.07	1.25	1.78	1.47	2.95	1.69	4.90
1.04	1.10	1.26	1.82	1.48	3.02	1.70	5.01
1.05	1.12	1.27	1.86	1.49	3.09	1.71	5.13
1.06	1.15	1.28	1.90	1.50	3.16	1.72	5.25
1.07	1.18	1.29	1.95	1.51	3.24	1.73	5.37
1.08	1.20	1.30	2.00	1.52	3.31	1.74	5.50
1.09	1.23	1.31	2.04	1.53	3.39	1.75	5.62
1.10	1.26	1.32	2.09	1.54	3.47	1.76	5.75
1.11	1.29	1.33	2.14	1.55	3.55	1.77	5.89
1.12	1.32	1.34	2.19	1.56	3.63	1.78	6.03
1.13	1.35	1.35	2.24	1.57	3.72	1.79	6.17
1.14	1.38	1.36	2.29	1.58	3.80	1.80	6.31
1.15	1.41	1.37	2.34	1.59	3.89	1.81	6.46
1.16	1.44	1.38	2.40	1.60	3.98	1.82	6.61
1.17	1.48	1.39	2.46	1.61	4.07	1.83	6.76
1.18	1.51	1.40	2.51	1.62	4.17	1.84	6.92
1.19	1.55	1.41	2.57	1.63	4.27	1.85	7.08
1.20	1.59	1.42	2.63	1.64	4.37	1.86	7.24
1.21	1.62	1.43	2.69	1.65	4.47	1.87	7.41

7.2 HTPQ test specimen section size from a successful HTPQ test together with the overall D_I value for that material indicates other alloy D_I and section sizes that are pre-qualified. All combinations of alloy D_I values of section sizes with lesser or equal quench severity values than for the successful HTPQ test, as determined with Table IV for plates or Table V for round sections, are pre-qualified

Table IV: HTPQ Quench Severity Values as a function of overall alloy D_I and the HTPQ thickness that has passed qualification testing.

Overall D_I(in)	**Qualification Section Thickness (in)**							
	0.25	**0.5**	**1**	**2**	**3**	**4**	**6**	**10**
15	0.00	0.00	0.01	0.02	0.03	0.04	0.06	0.29
14	0.00	0.00	0.01	0.02	0.04	0.05	0.11	0.73
13	0.00	0.00	0.01	0.02	0.04	0.06	0.16	0.68
12	0.00	0.00	0.01	0.03	0.05	0.08	0.22	1.14
11	0.00	0.00	0.01	0.04	0.06	0.09	0.26	1.11
10	0.00	0.00	0.02	0.04	0.08	0.15	0.44	2.17
9	0.00	0.00	0.02	0.06	0.10	0.17	1.75	∞
8	0.00	0.01	0.03	0.07	0.15	0.32	∞	
7	0.00	0.02	0.04	0.11	0.25	0.55		
6	0.00	0.02	0.05	0.17	0.38	2.59		
5	0.00	0.02	0.09	0.34	1.01	∞		
4	0.00	0.05	0.14	0.62	∞			
3	0.04	0.12	0.35	2.30				
2	0.13	0.37	1.52	∞				
1	0.72	2.29	∞					

Table V: HTPQ Quench Severity Values as a function of overall alloy D_I and the HTPQ diameter that has passed qualification testing.

Overall D_I (in)	Qualification Section Diameter (in)									
	0.25	**0.5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
15	0.00	0.00	0.01	0.01	0.02	0.03	0.04	0.04	0.05	0.06
14	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.06	0.08	0.10
13	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.08	0.11	0.15
12	0.00	0.00	0.01	0.02	0.03	0.05	0.06	0.09	0.14	0.21
11	0.00	0.00	0.01	0.02	0.04	0.06	0.08	0.11	0.16	0.24
10	0.00	0.00	0.01	0.03	0.05	0.08	0.12	0.19	0.28	0.42
9	0.00	0.00	0.01	0.04	0.07	0.09	0.13	0.21	0.32	1.33
8	0.00	0.01	0.02	0.05	0.09	0.14	0.24	0.46	1.16	9.38
7	0.00	0.01	0.03	0.07	0.13	0.23	0.38	1.15	7.99	∞
6	0.00	0.01	0.03	0.10	0.20	0.38	0.78	7.70	∞	
5	0.00	0.01	0.05	0.15	0.39	0.76	6.69	∞		
4	0.00	0.02	0.10	0.33	0.82	8.14	∞			
3	0.02	0.08	0.20	0.84	3.42	∞				
2	0.08	0.28	0.58	10.24	∞					
1	0.50	1.48	6.15	∞						

Appendix C

Standard Practice for Qualification of Heat Treatment Procedures for Nickel-Base and High Alloy Steel Castings

[DRAFT—September 28, 2004]

1.Scope

1.1 This practice establishes the qualification of procedures for the heat treatment of high alloy steel castings and nickel-base alloy castings.

1.2 Each manufacturer or contractor is responsible for the heat treatment performed by the organization and shall conduct the testing required to qualify a heat treatment procedure. Castings successfully heat treated within the scope of these procedures may use the 'HTPQ' (heat treatment procedure qualified) designation.

1.3 Each manufacturer or contractor shall maintain a record of all heat treatment qualification tests.

1.4 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents: therefore, each system must be used independently of the other. Combining values from the two systems may result in non-conformance with this practice.

2. Referenced Documents

ASTM A985 ASTM A957 ASTM A781 ASTM A703 ASTM A370 ASTM E8

3. Terminology

3.1 Heat treatment cycle: The sequence and type of thermal events, which may be used to produce a particular property, which could be either mechanical, corrosion or, a combination of mechanical and corrosion.

3.3 Heat treatment events: Heat treatment events include the following:

3.2.1 Austenitize – heating an alloy above the transformation temperature to form austenite.

3.2.2. Solutionize/Anneal - heating to a temperature high enough to dissolve carbides.

3.2.3 Homogenize – a pre-heat treatment heating to a temperature high enough and holding the alloy at the temperature for a sufficient amount of time to reduce chemical segregation.

3.2.4 Quench - rapid cooling from the austenitizing/solutionizing temperature. The part may be cooled in a liquid or rapidly moving air or gas.

3.2.5 Furnace Load Density - Total weight of the casting loaded into the heat treatment furnace divided by the working volume of the heat treatment furnace.

3.2.6 Local Load Density – Weight of a grouping of castings consolidated in a local region of the heat treatment furnace divided by the volume of the consolidated group of castings.

4 Heat Treatment Procedure Qualification

4.1 Test Blocks: Heat Treatment procedure qualification test castings may be selected from ASTM A703, A781, A957 or A985, alternative test block designs required by other material standards, or separately cast test plates. The section size of the test block shall be the maximum section thickness qualified. The alloy grade of the heat from which the test blocks are poured shall be recorded.

4.2 Preparation of test specimens: Mechanical and corrosion performance test coupons shall be machined from the test block sections after undergoing the specified thermal cycle.

4.3 Types of Tests

Tension test
Charpy impact test
Corrosion test

4.3.1 Tension Test

4.3.1.1 One tension test shall be performed and conform to the tensile requirements required in the material specification, test bars shall be prepared from the test block according to ASTM E8.

4.3.1.2 If the specimen shows defective machining or develops flaws, it may be discarded and another substituted from the same heat treatment procedure qualification test casting. In the event that the mechanical performance of specimens fails to meet the acceptance standard, two additional test specimens may be taken from the same block and retested. Should either set of test fail to meet the requirements, then the procedure is not qualified.

4.3.2 Corrosion Test: Corrosion testing will be carried out, in accordance with the requirements of ASTM. In the event that the corrosion performance of specimens fails to meet the acceptance standard, two additional test specimens may be taken from the same block and retested. Should either set of tests fail to meet the requirements, the procedure is not qualified.

4.3.3 Charpy Impact Test: Charpy impact tests may be carried out in accordance with the requirements of ASTM A370.

5. Heat Treatment Procedure Qualification (HTPQ) documentation

5.1 Material: The alloy grade of the steel for heat treatment procedure qualification shall be recorded along with the section size of the test block.

5.2 Furnace loading: Heat treatment procedure qualification trials must be conducted on loaded furnaces with test plates located both in the center and at the edge of the load for each stage of the heat treatment cycle. The load weight, the furnace load density, and the local load density shall be recorded.

5.3 Qualification Procedures: Heat treatment procedure qualification testing is to be performed using one of the following HTPQ procedures:

A5.4 Procedure A – Single Furnace HTPQ: Procedure A is used to qualify a particular heat treatment furnace or heat treatment furnace combination for multistage heat treatments. It does not require the instrumentation of actual heat treatment loads during heat treatment qualification procedures or during subsequent qualified heat treatments.

A5.4.1 Qualification Temperature: The reported qualification temperature shall be recorded as the furnace thermal treatment temperature.

A5.4.2 Qualification Time: The reported qualification time shall be reported as the total time at the furnace thermal treatment temperature.

A5.4.3 Transfer time: The transfer time for removal from the furnace to the onset of cooling/quenching shall be recorded for quenching only. Transfer time during quenching is measured from the time the furnace door is opened until the furnace load is completely immersed in the quenchant.

A5.4.4 Quenching: The quenchant temperature shall be measured immediately prior to and immediately after the load has been quenched. The immersion time of the HTPQ load in the quench tank shall be recorded. Quenchant velocity shall be measured immediately prior to testing at a quench tank location without any casting load in the quench tank.

A5.4.5 Cooling: If forced air or gas cooling instead of quenching is employed, the air or gas velocity should be measured and recorded.

A6. Re-qualification of a heat treatment procedure: A heat treatment procedure must be re-qualified when any of the changes listed below are made. Changes to heat treatment procedures other than those listed, may be made without re-qualification. Furnace controllers must be calibrated every six months to retain HTPQ certification.

A6.1 A different heat treatment furnace to the one already qualified is used.

A6.2 A change in furnace design involving the method of firing, furnace insulation, shape changes to the furnace working volume

A6.3 A furnace load density or local load density greater than 110% of the load densities used during qualification

A6.4 A decrease in the furnace thermal treatment temperatures or a decrease in the furnace thermal treatment hold time.

A6.5 A change in quenchant, quench tank design or agitation system design that decreases quench severity.

A6.6 An increase in the quench delay time by more than 25%. An increase in the forced air or gas cooling delay time during normalizing by more than 50%

A6.7 An increase in the final quench tank temperatures above 110 F. If the HTPQ final quench tank temperature was greater than 110 F, then the final quench tank temperature during qualification is the maximum acceptable quench tank temperature

A6.8 A change in alloy composition and/or section size that results in a decreased effective quench severity as determined in Table A1 for the various high alloy steels

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B5.4 Procedure B – Multiple Furnace HTPQ: Multiple Furnace HTPQ: Procedure B is used to qualify heat treatments based on temperature measurement from furnace load thermocouples. It requires the temperature instrumentation of actual heat treatment furnace loads during heat treatment procedure qualification testing.

B5.4.1 Qualification Temperature: The reported thermal treatment temperature shall be the temperature recorded by a thermocouple placed at the center of the casting load (load thermocouple) during qualification testing. The reported thermal treatment time shall be reported as the hold time (time at temperature) of the load thermocouple. Te corresponding furnace thermal treatment temperature and time at temperature shall also be recorded.

B5.4.2 Transfer time: The transfer time for removal from the furnace to the onset of cooling/quenching shall be recorded for quenching only. Transfer time during quenching is measured from the time the furnace door is opened until the furnace load is completely immersed in the quenchant.

B5.4.3 Quenching: The quenchant temperature shall be measured immediately prior to and immediately after the load has been quenched. The immersion time of the HTPQ load in the quench tank shall be recorded. Quenchant velocity shall be measured immediately prior to testing at a quench tank location without any casting load in the quench tank.

B5.4.4 Cooling: When cooling other than quenching is employed, all cooling cycle operating parameters governing the cooling rate and extent of cooling shall be measured and recorded.

B6. Re-qualification of a heat treatment procedure: A heat treatment procedure must be re-qualified when any of the changes listed below are made. Changes to heat treatment procedures other than those listed may be made without re-qualification. Furnace controllers must be calibrated every six months to retain HTPQ certification.

B6.1 An increase in furnace load density or local load density greater than 110% of the load densities used during qualification.

B6.2 An increase in casting section size beyond the qualification test block section size.

B6.3 A decrease in the thermal treatment qualifying temperature or a decrease in the qualifying hold time as indicated by load thermocouples or by the corresponding furnace temperature and time at temperature.

B6.4 A change in quenchant, quench tank design or agitation system design that decreases quench severity.

B6.5 An increase in the quench delay time by more than 25%. An increase in the furnace air or gas cooling delay time during normalizing by more than 50%.

B6.6 An increase in the final quench tank temperatures above 110 F. If the HTPQ final quench tank temperature was greater than 110 F, then the final quench tank temperature during qualification is the maximum acceptable quench tank temperature.

B6.7 A change in alloy composition and/or section size that results in a decreased effective quench severity as determined in Table A1 for the various high alloy steels

B6.8 The use of other heat treatment furnaces, changes in furnace treatment temperatures or time at temperature that reduce the load thermal treatment temperature or time at temperature used for qualification.

B6.9 When the furnace thermal treatment temperature and furnace thermal treatment time at temperature for any furnace used for thermal treatment cannot be linked to the expected load thermocouple temperature and load thermocouple time at temperature.

All high alloy steels considered are ranked according to difficulty of heat treatment and grouped together in alloy groups with similar heat treatment characteristics. Successful HTPQ of an alloy grade in a group and section size from Table I prequalifies alloys with less demanding heat treatment requirements and section size combinations as determined with Table II.

AUSTENITIC GRADES

Table AI: Rating of austenitic high alloy steels by ease of heat treatment. Alloys in the same group have similar heat treatment performance. (Group 'A-A' grades of material are the easiest to heat treat. Group 'A-D' grades of material are the most difficult to heat treat.)

Group	Alloy
A-A	CE-30
	CF-16Fa
	CF-16F
A-B	CF-3M
	CF-20
	CF-10SMnN
	CF-8
	CF-8M
A-C	CF-3
	CF3-Mn
	CF-8C
	CG-12
	CG-6MMn
	CG-3M
	CG-8M
A-D	CG-3M
	CG-8M

Table A-II: HTPQ ratings for austenitic high alloy steels. Successful HTPQ of an alloy group and section size from this table pre-qualifies all other alloy group and section size combinations listed in the same row or in rows located above.

	Section Size			
	<1 in.	1 in. to <2 in.	6 in. to < 10 in.	<10 in.
Group	A-A			
	A-B	A-A		
	A-C	A-B	A-A	
	A-D	A-C	A-B	A-A
		A-D	A-C	A-B
			A-D	A-C
				A-D

DUPLEX GRADES

Table D-I: Ranking of duplex high alloy steels by ease of heat treatment. (Group 'D-A' grades of material are the easiest to heat treat. Group 'D-C' grades of material are the most difficult to heat treat.)

Group	Alloy
D-A	3A 1C 4A
D-B	1B 1A
D-C	CD-4MCu 5A 6A

Table D-II: HTPQ ratings for duplex high alloy steels. Successful HTPQ of an alloy group and section size from this table pre-qualifies all other alloy group and section size combinations listed in the same row or in rows located above.

	Section Size			
	1in	2in	6in	10in
Group	D-A			
	D-B	D-A		
	D-C	D-B	D-A	
		D-C	D-B	D-A
			D-C	D-B
				D-C

FERRITIC GRADES

Table F-I: Rating of ferritic high alloy steels by ease of heat treatment. Alloys in the same group have similar heat treatment performance. (Group 'F-A' grades of material are the easiest to heat treat. Group 'F-B' grades of material are the most difficult to heat treat.)

Group	Alloy
F-A	CB-6 CB-30
F-B	CC-50

Table F-II: HTPQ ratings for ferritic high alloy steels. Successful HTPQ of an alloy group and section size from this table prequalifies all other alloy group and section size combinations listed in the same row or in rows located above.

	Section Size			
	1in	2in	6in	10in
Group	F-A			
	F-B	F-A		
		F-B	F-A	
			F-B	F-A
				F-B

MARTENSITIC GRADES

Table M-I: Rating of martensitic high alloy steels by ease of heat treatment. Alloys in the same group have similar heat treatment performance. (Group ‘m-A’ grades of material are the easiest to heat treat. Group ‘M-C’ grades of material are the most difficult to heat treat.)

Group	Alloy
M-A	CA-28MWV
M-B	CA-15M CA-6NM CA-40F CA-6N
M-C	CA-15 CA-40

Table M-II: HTPQ ratings for martensitic high alloy steels. Successful HTPQ of an alloy group and section size from this table pre-qualifies all other alloy group and section size combinations listed in the same row or in rows located above.

	Section Size			
	1in	2in	6in	10in
Group	M-A			
	M-B	M-A		
	M-C	M-B	M-A	
		M-C	M-B	M-A
			M-C	M-B
				M-C

SUPER AUSTENITIC GRADES

Table SA-I: Rating of super austenitic high alloy steels by ease of heat treatment. Alloys in the same group have similar heat treatment performance. (Group 'SA-A' grades of material are the easiest to heat treat. Group 'SA-D' grades of material are the most difficult to heat treat.)

Group	Alloy
SA-A	CF-10 CH-10 CH-8 CH-20 CF-10SMnN CK-20
SA-B	CF-10M CF-10MC CE-20N
SA-C	CT-15C CN-7M CN-3M
SA-D	CK-3MCuN CN-7MS

Rank order of quench severity

Table SA-II: HTPQ ratings for super austenitic high alloy steels. Successful HTPQ of an alloy group and section size from this table pre-qualifies all other alloy group and section size combinations listed in the same row or in rows located above.

	Section Size			
	1in	2in	6in	10in
Group	SA-A			
	SA-B	SA-A		
	SA-C	SA-B	SA-A	
	SA-D	SA-C	SA-B	SA-A
		SA-D	SA-C	SA-B
			SA-D	SA-C
				SA-D