YEARLY PROGRESS REPORT

Project Title: Heat Treatment Procedure Qualification for Steel Castings

Covering Period: September 30, 2001 through September 29, 2002

Date of Report: February 2, 2003

Recipient: Penn State University
310 Leonhard Building
University Park PA 16802

Award Number: DE-FC07ID13841

Subcontractors: none

Other Partners: Steel Founders' Society of America (SFSA) and SFSA member foundries

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Project Objective: To develop and validate heat treatment procedure qualification guidelines that can be used by steel foundries and steel casting customers for heat treatment quality assurance. These guidelines as similar in principle to weld procedure qualification procedures widely used for high-performance weldment applications.

Background: American Society for Testing and Materials (ASTM) specifications for both high alloy and low alloy steel castings call out composition limits and some heat treatment requirements. However, meeting these ASTM specification targets regarding heat treatment does not assure casting performance. Past experiences have shown that cast components with less than adequate microstructures and service performance will still meet specifications. It is therefore necessary to pioneer and develop "heat treatment procedure qualifications (HTPQ) guidelines that can be used by foundries to demonstrate and assure casting performance. This work addresses a key industry challenge to correlate test bar properties with casting performance, and substantially reduces energy costs for re-heat treatment and plant stoppages due to casting failures.

Status:

The fundamental relevant heat treatment practices and variables that are expected to control heat treatment performance in the steel foundries were reviewed. These heat treatment parameters were categorized based on their relevance to the heat treatment procedure qualification (HTPQ) development and were expressed in terms of fundamental variables. A summary of comprehensive HTPQ development trials from recent studies at two SFSA member foundries are presented. These comprehensive trials at the foundries are also being used to quantify the influence of the heat treatment variables in practices on the treatment performance.

Introduction

Significant differences exist in current heat treatment practice used by SFSA member foundries. The heat treatment pre-qualification (HTPQ) methodologies offer the opportunity to develop and standardize robust heat treatment practices based on both fundamental principles and foundry-specific heat treatment practices. A preliminary list of heat treatment variables was presented at the Technical and Operating conference of the Steel Founders Society of America, in November 2002.

Process and equipment variables affect heat treatment response and the selection of appropriate HTPQ set points. A successful 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. For the purposes of HTPQ development, many critical heat treatment variables can be adequately expressed by load thermocouple time and temperature profiles. Expressing heat treatment variables in terms of a few fundamental variables also enables easier process control and monitoring.

Heat Treatment Procedure Qualification Trials

Comprehensive HTPQ development trials were conducted at two foundries. Quench and temper heat treatments were performed on 8600 series steels with a variety of section sizes and compositions with complete instrumentation. The procedures used for the HTPQ development trials were somewhat different at each foundry. They were tailored to the existing practices at the foundries and to production limitations during the heat treatment period. Typical furnace loadings were used at both foundries for the tests. Past temperature uniformity survey information provided by the foundries was studied prior to locating the test plates within the furnaces. Efforts were made to locate the test plates in regions of the furnace that were of critical interest.

Foundry A – HTPQ Trials and Results

The test plates were located in the furnace on racks containing a "typical" load during both austenitizing and tempering. In addition to the controller thermocouple readings, 11 load thermocouples were attached to the surface of the plates for both austenitizing and tempering. Standard foundry quench and temper heat treatment cycles were performed. Since the load contained a part mix having different section sizes, the heat treatment time for HTPQ was based for the largest section size. The furnace temperature profiles for austenitizing are shown in Figure 1.The load from the austenitizing furnace was quenched into the quench tank water at 84 F. The quench delay (the time from opening the furnace door to the time at which the load was completely immersed in the quench tank) was 2 minutes. The resultant as-quenched hardness was measured for 6 plates from the test, Table 1. Internal specifications called for an as-quenched hardness of not less than 300HB. This can be compared to a calculated as-quenched hardness of 399HB. These lower than expected quenched hardness values are certainly due to the unacceptable low peak temperatures at certain furnace locations. The test plates were subsequently tempered at 1150F. Although re-orientation of the test plates before tempering to mimic all important extreme heat treatment conditions was called for, this was not possible to implement. Plates remained in the same furnace and load orientations during tempering. During tempering the tempering time of the largest section size, 4 inches determined the total tempering time at temperature for the entire load. Tempering hold time was specified as 4 hours (1 hour per inch of section). With an hour for ramp up, the total tempering time was 5 hours. The temperature profiles for tempering are shown on Figure 2. These temperature profiles show similar temperature uniformity problems and long ramp up times for certain furnace locations. Furnace temperature variations of 250F were observed for the various furnace and load locations during tempering.
Table 2 shows the results of the heat treatment procedure qualification for Foundry A. Tensile tests of test bars machined from the HTPQ plates indicates that only 2 of the plates tested met target property values for all of the properties evaluated.

Foundry B – HTPQ Trials and Results

Similar comprehensive HTPQ development trials were conducted at a second foundry. Three different grades of 8600 steel with somewhat different chemical compositions in 2, 4 and 6 inch section sizes were used for the trials. Standard quench and temper heat treatment cycle as well as "short cycle" heat treatments were evaluated. These heat treatments were conducted with only the test plates present in the furnace. No

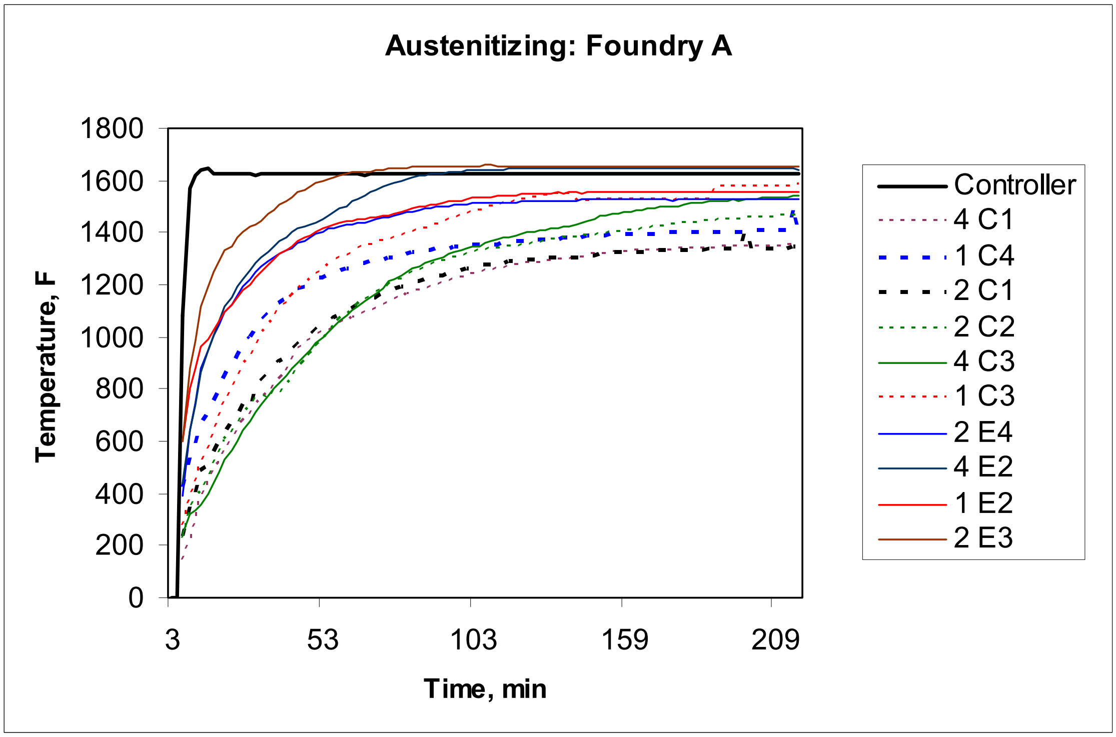

Figure 1: Austenitizing temperature profiles, Foundry A.

Table 1. As-Quenched test plate hardness Foundry A.

Plate ID	As-Quenched Hardness, HB	Final Hardness, HB
4C1	269	-
4E2	286	213
4C3	-	207
4E4	-	207
2C1	-	-
2C2	286	233
2E3	286	205
2E4	-	237
1E1	-	-
1E2	321	260
1E2	-	222
1C4	286	240

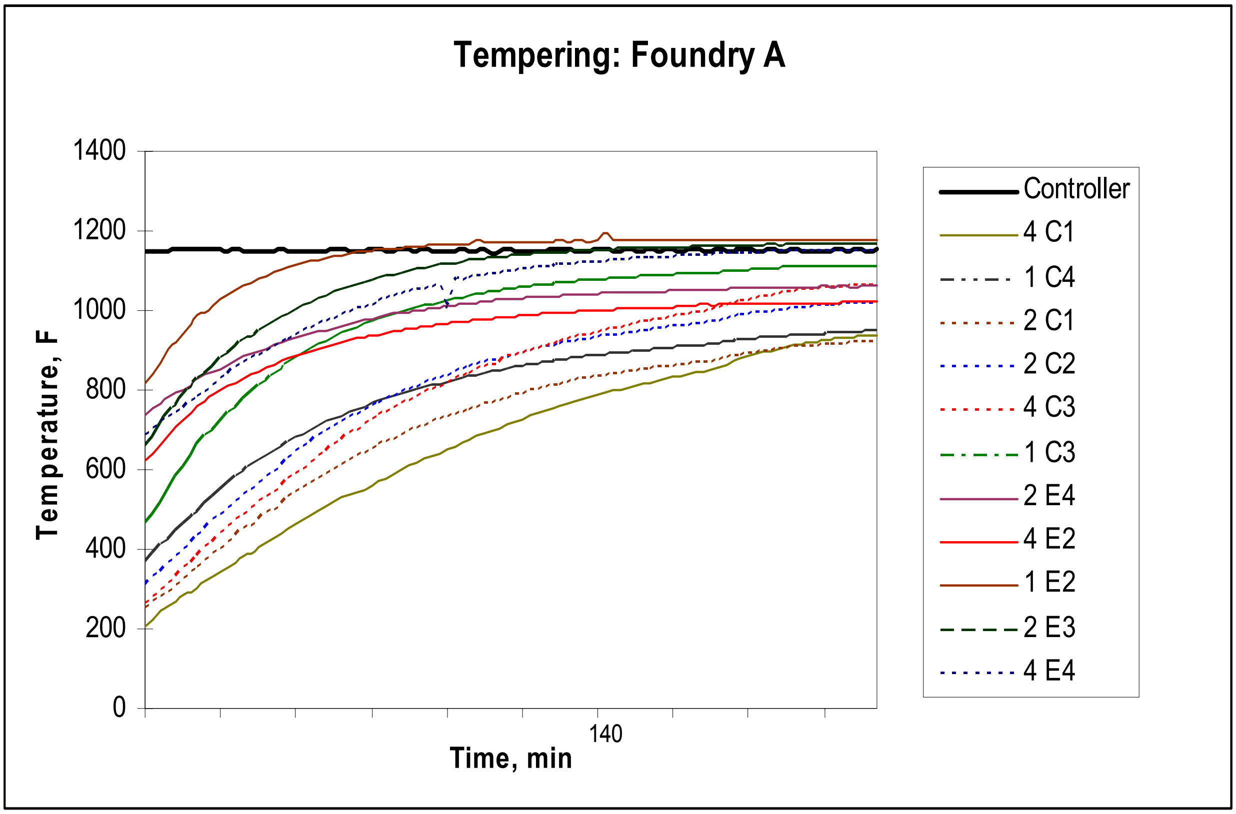

Figure 2: Tempering temperature profiles, Foundry A.

Table 2. HTPQ results for Foundry A.

ID/Target	Tensile (ksi)	Yield (ksi)	Elongation (%)	Reduction in Area (%)	Impact Toughness (ft-lbs.)
	105	85	17	35	20
4C1	95	64.5	21	20	4
4E2	102.5	77.5	11	25	14
4C3	98.5	67	13	22	22
4E4	99.5	74.5	13	25	18
2C1	92.5	62.5	15	16	6
2C2	112	81	13	17	6
2E3	98.5	75	14	30	20
2E4	114	90.5	8	20	9
1E1	125	102	17	29	13
1E2	107	85	24	47	28
1C3	115.5	94	20	44	30
1C4	103	68.5	12	18	5

additional castings were incorporated into the furnace load. This procedure mimics the standard furnace loading practices of Foundry B. During austenitizing, the castings were held for “half an hour per inch” of section size after attaining set point temperatures, as recorded by load thermocouples. Temperature profiles from the load thermocouples during austenitizing shown in Figure 3 suggests that temperature uniformity was very good through out the furnace. Also, test castings with the same section size had similar temperature-time ramp up cycles independent of load position in furnace. The furnace was opened and plates were periodically removed from the furnace and quenched at the desired austenitizing times. This scheme permitted a number of HTPQ runs to be conducted in the same furnace for test plates with different required hold times.

Test plates were removed from the furnace at different intervals of time and quenched into the quench tank operating at 95 F. The average quench delay recorded was 75 s. The quenched hardness was measured and compared against internal heat treatment quality control specifications, (Table 3). Most test plates achieved the desired as-quenched hardness values.

The relative positions of the test plates were shifted in the furnace prior to tempering, to study the effect of heat treating times on test plate properties. A two inch plate was tempered for the same time as the 4 inch plate and a 4 inch plate was tempered with the 6 inch plates. The set point temperature was 1250 F. The time in the furnace included the time for ramp up to the set point and a hold time of one hour per inch of section. Figure 4 shows the temperature profiles during tempering. All 12 test plates were heat treated with load thermocouples attached during tempering. The thermocouple information indicates excellent temperature uniformity during tempering. Initial ramp up was dependent on section size of casting rather than location of the casting in the furnace.

The analysis of the tempered hardness values obtained during HTPQ trials at both foundries show that temperature uniformity during tempering is of critical importance to the final properties of the casting. A tempering temperature variation of 250 F in Foundry A produced a large variation in final tempered hardness values (205-260 HB) that were considerably less than the expected theoretical hardness values. Variations in alloy composition and in tempering time and temperature can be expected to influence the final tempered hardness. The tempered hardness results from HTPQ studies have been compared to hardness predictions from tempering models in the literature. The final tempered hardness values for Foundry B had hardness variations that approached the predicted tempered hardness values, thus validating existing temper models, which will later be used for developing the qualification procedure document.

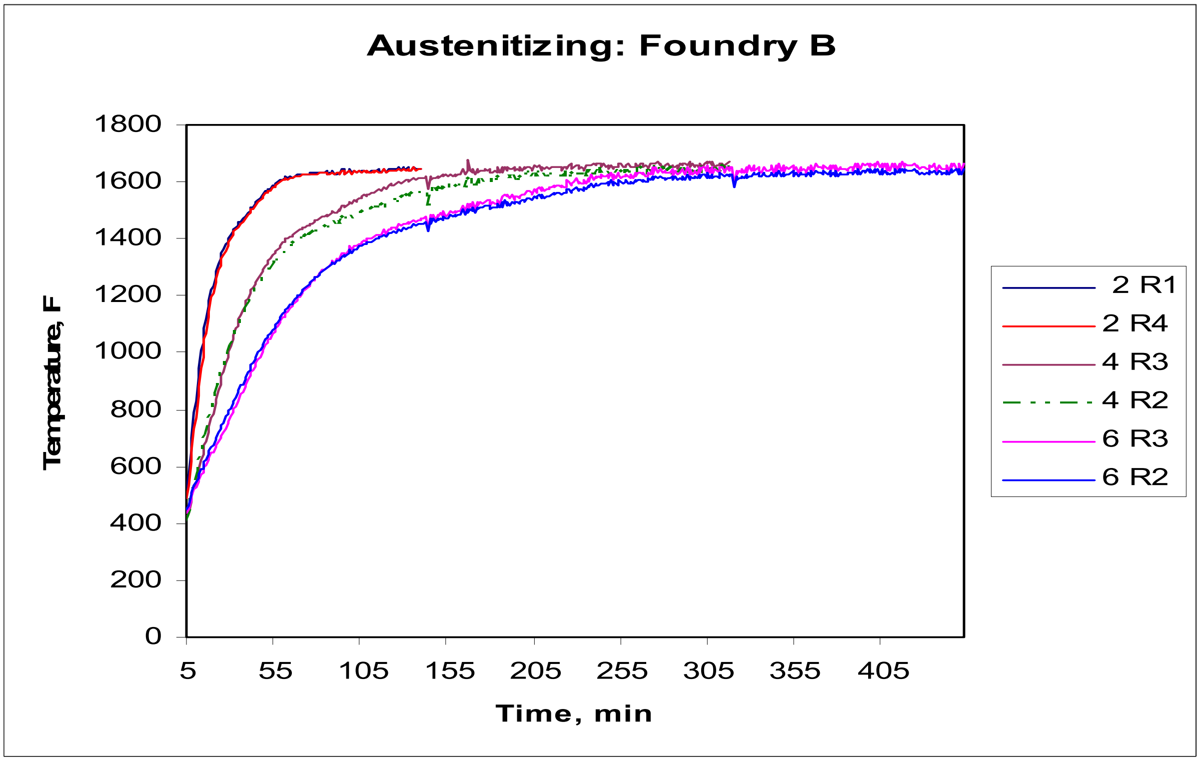

Figure 3: Austenitizing temperature profiles, Foundry B.

Table 3. As-Quenched and final hardness values for test plates, Foundry B.

Plate ID	As-Quenched Hardness, HB	Final Hardness, HB
6 R1	444	250
6 R2	514	230
6 R3	477	230
6 R4	477	250
4 R1	474	212
4 R2	474	212
4 R3	474	230
4 R4	432	230
2 R1	415	229
2 R2	363	217
2 R3	401	229
2 R4	388	217

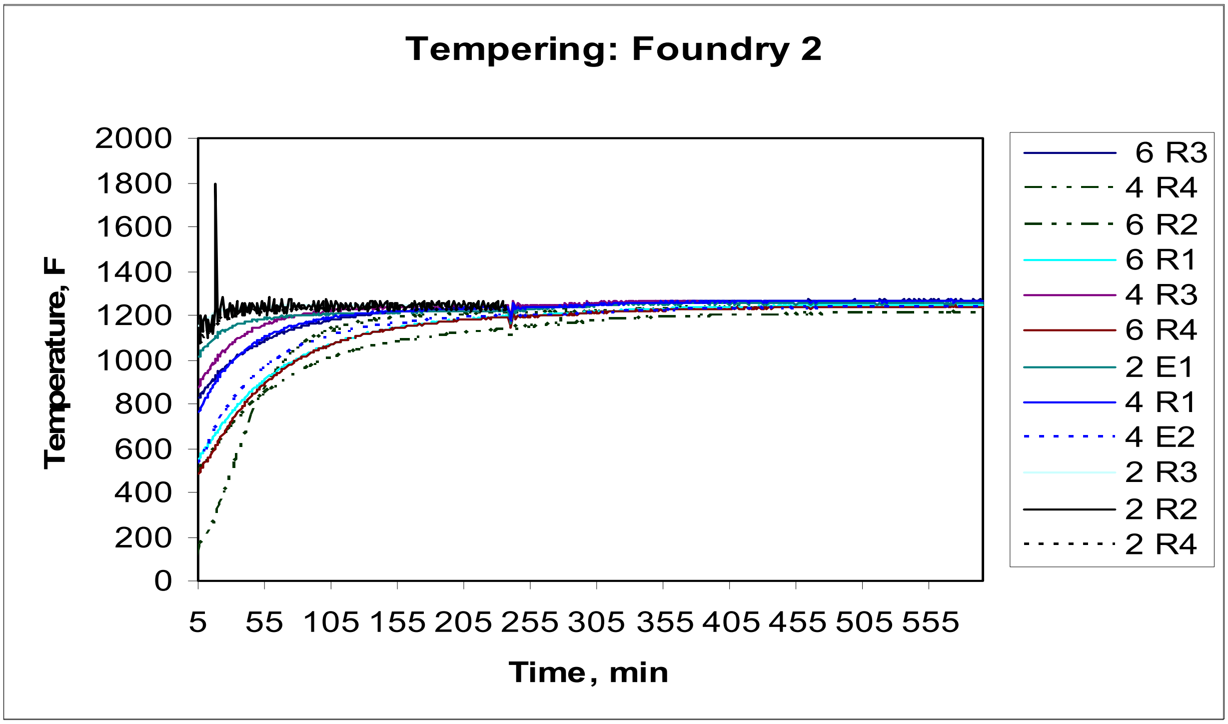

Figure 4: Tempering temperature profiles, Foundry B.

Plans for Next Year:

Data collection from all Procedure Qualification trials will be completed and final test results will be compared with existing theoretical models. A set of tempering trials will be conducted at the Penn State FAME lab. Test specimens of low and medium carbon alloy steels will be heat treated and the results obtained will be used to evaluate the accuracy of existing empirical models. Effects of temperature, ramp up time and hold time on mechanical properties will be studied. The trials will help verify and validate existing temper models. A statistical analysis will be performed on the results of the trials which will help modify existing tempering models to assist in accurate prediction of tempered hardness. The potential for short cycle heat treatment will also be looked at. Control strategies to reduce ramp up time of the furnace load will be investigated. A final working heat treatment procedure qualification will be established.

Patents: none

Milestone Status Table:

Program Title: Conservation R&D (CFDA 81.086)
Project Title: Heat Treatment Procedure Qualification for Steel Castings
Project ID No. DE-FC07-97ID13841

As of 9/29/02

ID #	Description	Planned Completion Date	Actual Completion Date	Comments
1	Qualification Methodologies	12/31/00	12/20/00	100% complete
1.1	Current specification review	3/31/00	6/30/00	100% complete
1.2	Develop qualification strategies	12/31/00	12/31/00	100% complete
2	Production qualification assessment	4/30/03		80% complete
2.1	Identify plant sites	4/31/00	7/15/00	100% complete
2.2	Characterize part histories	2/27/03		95% complete
2.3	Supervise qualification trials	4/30/03		65% complete
3	Develop qualification procedures	8/31/03*		75% complete
3.1	Document qualification procedures	10/31/02	10/20/02	100% complete
3.2	Establish qualification procedures	8/31/02		70% complete
4	Reporting	9/29/03		50% complete
4.1	Program manager review	9/29/03		50% complete
4.2	Reports and reviews	9/29/03		66% complete
4.3	Qualification procedure monograph	9/29/03		

Budget data: (As of 9/29/02)

Program Title: Conservation R&D (CFDA 81.086) DE-FC07-97ID13841 Project Title: Heat Treatment Procedure Qualification for Steel Castings								
			Approved Spending Plan			**Actual Spent to Date**		
Phase/Budget Period			***DOE Amount***	***Cost Share***	***Total***	***DOE Amount***	***Cost Share***	***Total***
	From	***To***						
Year 1	1/1/00	12/31/00	126,152	132,000	258,152	23,332	42,400	65,732
Year 2	1/1/01	12/31/01	163,098	132,000	295,098	30,961	29,400	60,361
Year 3	1/1/02	9/29/02	97,783	132,000	229,783	97,713	175,600	273,313
Year 4*	1/1/03	9/29/03	-	-	-			
Totals			387,033	346,000	783,033	152,006	247,400	399,406

* All amounts in US Dollars. Year 4 shows the approved no-cost extension.

Spending Plan for the Next Year

Month	Estimated Spending
January	$15,000
February	$15,000
March	$150,000
April	$15,000
May	$30,000
June	$30,000
July	$30,000
August	$20,000
September	$20,000
October	$15,000
November	$15,000
December	$15,027