Improving productivity and energy efficiency in the heat treatment of steel castings

by

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Signatures have been redacted for privacy

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Abstract

To ensure a successful austenitizing heat treatment, the steel casting industry has used conservative practices. The long process times result in inefficient use of time and energy. Past research has justified the application of shorter process times, but industry has been unable to implement their findings because of control limitations. The problem is identifying when the load has reached temperature. This paper discusses the disconnect between the recommended heat treatment process strategy and the control strategy and proposes an improved control strategy. The firing rate or output signal from the controller is introduced as a novel approach to identify indirectly when the load has finished soaking. This work has demonstrated potential savings of 30% in process time and gas consumption with each load.

Disclaimer

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1 Introduction

The steel casting industry produces parts with complex geometries that are unattainable through other manufacturing processes. The industry utilizes the flexibility of a job shop setup to handle the wide variety of jobs ordered in small production quantities. Parts size can range from a few pounds to a few thousand pounds with relatively simple designs such as brackets or to intricate shapes such as valves. Additionally, the steel chemistry of each job can be modified to meet consumer needs such as preventing corrosion or minimizing material costs.

Heat treatment is a critical step in the manufacturing process because it enhances material properties and enables the part to meet performance requirements. The process is inherently energy and time intensive since temperature gradients are used to drive heat into the castings to reach required temperatures. The part is soaked at this temperature for a specified time, and then cooled at prescribed rates to achieve the desired microstructure and properties.

Because heat treatment is critical to the final product, much effort has been expended to understand and improve the process. Research has been conducted to identify times and temperatures needed for sufficient heat treatment of various materials and section sizes[1,2]. Advancements in furnace design have improved the steady state temperature uniformity of unloaded furnaces. Accurate simulations of heat treatment loads are possible with the improvements in computing technology[3].

Yet with this information, the steel casting industry and their customers continue to utilize conservative practices instead of implementing the results from research. Many facilities still employ rules such as '1-hour-per-inch' for soaking times[2,4,5] once the furnace reaches temperature or another empirical relationship based on the load's largest section size. The application of these rules results in longer than necessary process times and inefficient energy usage since they are designed to encompass any potential variability. Ample evidence strengthens the grounds for improving upon these conservative practices. Moreover, optimizing energy usage has become a topic of considerable scrutiny with the surge in natural gas costs and market uncertainties; yet, the industry still has been slow to implement practices that are more aggressive. No robust method exists to accurately know when soak time in austenitizing heat treatments has come to completion. Without an improved method that is applicable industry-wide to replace the '1-hour-per-inch' rule of thumb, the practice will persist.

Research has partially justified the removal of this rule from specifications with a recommendation of a shorter process strategy. The obstacle to implementing the shorter process strategy has been inadequate instrumentation in industry. Instrumentation is the combination of a control strategy that determines which variables to assess and the sensors that measure those variables. Research has generated detailed time-temperature process strategies for heat-treating of steel castings; however, industry uses control strategies that are associated to the controller's limitations and not the process requirements. Measurements from the sensors fit the need of the controller, but are unable to satisfy the process strategy. This paper addresses the issue of inadequate instrumentation by reviewing the process strategy for austenitizing temperature heat treatments of carbon and low alloy steel castings. Then, the control strategy is compared to the process strategy to demonstrate its failure to meet the requirements put forth by research, and finally a novel approach is proposed to align the two strategies. The approach outlined is applicable to other batch heating processes with slow responses.

2 Review of Heat Treatment Strategies

2.1 Conservative Practices

For many years, the steel casting industry has utilized conservative practices in heat-treating in the austenite region. The rule of thumb was to heat the furnace to some temperature above 1400 F, and then maintain the furnace at this temperature for "1-hour-per-inch" based on the largest cross section thickness in the load. The author has not identified the exact origin of this rule, but it may have arisen as a way to cope with poor equipment design in the past that lead to non-uniform heating[4]. Although its beginnings are not known exactly, past research has identified this practice as troublesome and has attempted to eliminate its usage. In 1958, Briggs[6] conducted research with this purpose in mind. He stated that:

> "...after the information of this report is available to the purchasers of steel castings, the 1-hour-per-inch rule will be discarded from specification..."

The application of this conservative practice continued in spite of Briggs' work as noted by additional work in 1981 to eliminate the practice. Patterson[7] investigated the mechanical properties of castings in shortened heat treatments. Based on his results, he concluded:

> "...that the information contained in this report will be an aid to the operators of foundries in their efforts to convince purchasers of steel castings that the 1-hour-per-inch rule is not metallurgically necessary."

Although Patterson's report amply demonstrated that heat treatment times could be shortened without degradation of mechanical properties, the industry continued using its conservative practices as before. Voigt[5] noted the continued usage of the '1-hour-per-inch' rule in his 2004 work to develop heat treatment qualification procedures. He documented that:

> "While most steel foundries use 1-hour-per-inch guidelines to establish proper heat treatment time, the practice of this rule varies between foundries."

His work did not attempt to eliminate the '1-hour-per-inch' rule but rather focused on standardizing the practices currently in place to ensure quality. For instance, Voigt[5] reported that many foundries use in-house standards or requirements as specified by the customers, which can vary based on the available standards. For example, ISO 683 recommends a soak time of one half hour for austenitizing once the casting has reached the appropriate temperature; whereas, ASM 2759 1c recommends soak times based on section thickness as shown in Table 1. The Steel Heat Treatment Handbook[2] mentions the current usage of the '1-hour-per-inch', but can only suggest other empirical methods that are furnace and load specific as solutions to replace the rule of thumb.

The purpose of these standards is to ensure that each load receives sufficient heat treatment. The methodology used to qualify a treatment is generally based on some correlation to section size. Although the focus is on time, temperature, and section size, a quality heat treatment requires more than that. A review of what is occurring in austenitizing heat treatments is appropriate to understand why these conservative rules are in place.

Table 1 Soak time for annealing, normalizing, and austenitizing based on section size in ASM 2759 1c[5].

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).

2.2 Process Strategy

The purpose of heat treatment is to modify the microstructure to obtain a wide variety of desired material properties without changing the chemical composition or shape[4]. There are many types of heat treatments that heat into the austenite region as a precursor to subsequent processing such as austenitizing, homogenizing, normalizing, annealing, and the heating prior to quenching. For carbon and low alloy steels, the castings are heated above 1340 F to obtain a uniform austenite grain size without coarsening, to attain a uniform structure, and to relieve internal stresses[1,14].

The change in material properties is possible because iron has different solid phase configurations. At high temperatures, it shifts from a body-centered cubic crystal (alpha ferrite) to a face-centered cubic crystal (gamma austenite) as shown in Figure 1. The process of shifting allows the solid to redistribute carbon and change its crystal size. Carbon interacts with iron by either dissolving into its crystal lattice or forming a hard, brittle compound called cementite or iron-carbide (Fe_3C). The concentration difference between each phase has the ability to redistribute carbon. The solubility of carbon in cementite is 25%, austenite is 2%, and ferrite is 0.025%[1]. By controlling the location and size of ferrite and cementite, the mechanical properties can be changed. Pearlite is bands of alternating ferrite and cementite.

Modifying the cooling rates from the austenite region alters the ferrite and cementite distribution. The key principle in the final microstructure is the rate of temperature change and its control on nucleation and grain growth[1]. Faster decreases in temperature generate more nucleation sites available for ferrite growth promoting finer microstructures and distributing the cementite more uniformly throughout the microstructure. Slower decreases in temperature promote ferrite grain growth and coarser microstructures. Thick layers of cementite are concentrated in locations surrounding the large ferrite crystals. Additionally, rapid temperature changes can trap the carbon in the ferrite phase to form martensite (body-center tetragonal crystal) [9].

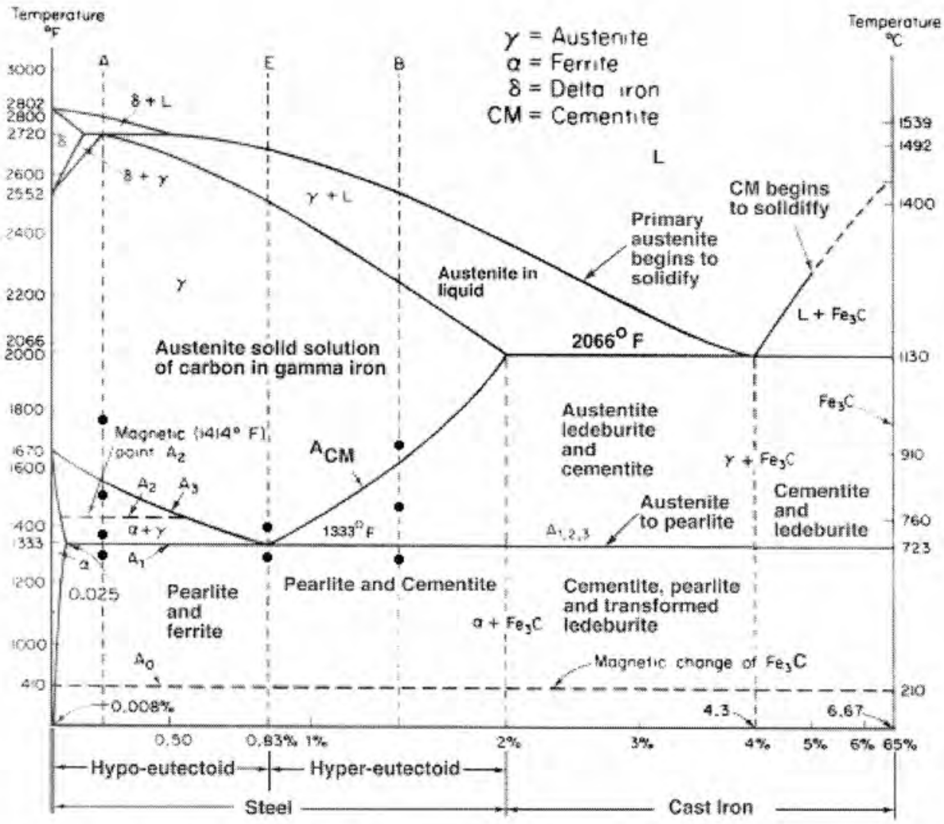


Figure 1 Fe-Fe$_3$C phase diagram[8].

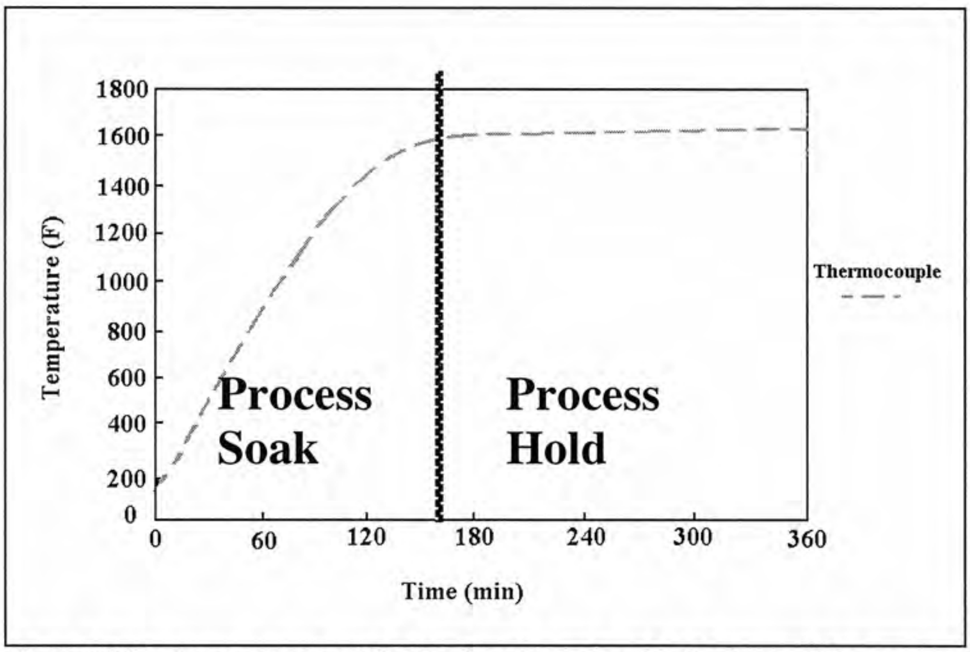


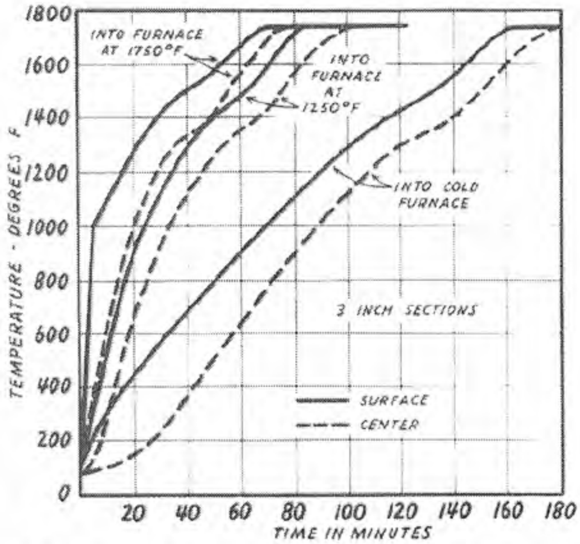
Figure 2 Time-temperature profile showing the soak and hold phases of the process strategy.

This paper will focus on the soaking portion of the process in identifying its completion in preparation for subsequent cooling. The process strategy centers around four considerations: heat soak delays, soaking temperature uniformity, austenite formation, and carbide diffusion[1,4]. The process strategy suggested by this research can be broken down into two distinct phases: process soak and process hold as shown in Figure 2. The thermocouple measurement shown represents a single casting's temperature. Process soak, not to be confused with soak mentioned previously, is the time required to bring the entire casting to a steady state in temperature. Heat transfer mechanisms determine its length. Process hold is the time needed to fully austenitize and diffuse carbides in the casting once at an equilibrium temperature. Phase transformations and diffusion mechanisms control its duration.

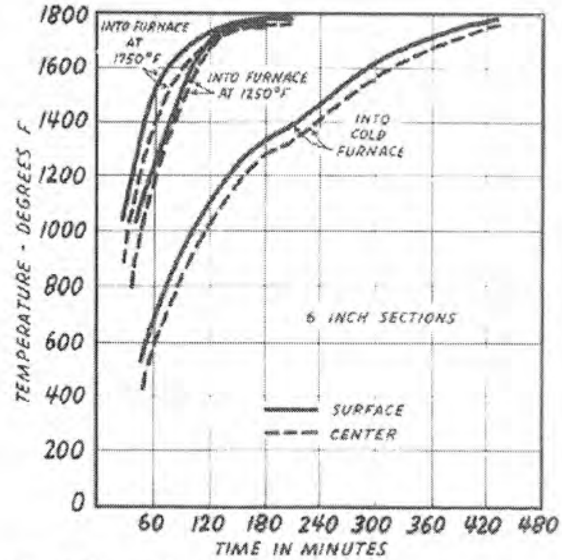
2.2.1 Process Soak Time and Temperature

The first considerations with the process strategy are related to the temperature of the load itself. Because of part geometry and load packing, delays in the time to reach the designated temperature are a reality of any heat treatment. The time required is a function of the heat transfer mechanisms, the current material state and properties, and the part geometry. Briggs[6] documented time difference from heating between the surface and center of 1", 3", and 6" sections for various low alloy steels as shown in Figure 3. The time difference between the surface and center sections to reach temperature was less than 30 minutes for all experiments. Patterson[7] measured the surface, quarter thickness, and centerline of a 5" low alloy steel block and found that individually heated blocks in a preheated furnace required about 72 minutes to reach equilibrium at 1700 F. The delay for the casting center was about 15 minutes.

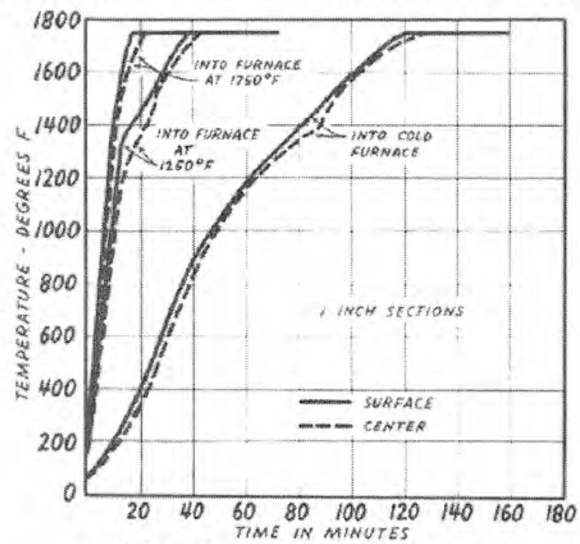
Aronov[10] documented the soak time variability for various loading configurations and packing densities including the temperature difference between the load and furnace air as shown in Figure 4. Key factors in the time to reach equilibrium are the influences of packing density and load orientation. Hanquist[11] investigated the effect that surface finish, location in the furnace, and load size has on soak time and difference in temperature to the furnace air for 3", 5", and 8" carbon steel castings. He suggested that the temperature monitored inside the furnace may not be indicative of the castings' temperature.



a) MnCrMo and MnB cast steels



b) CrMo and MnNiCrMo cast steels



c) MnCrMo and MnB cast steels

Figure 3 Heating of a) 3", b) 6", and c) 1" sections of alloy cast steels at 1750 F.

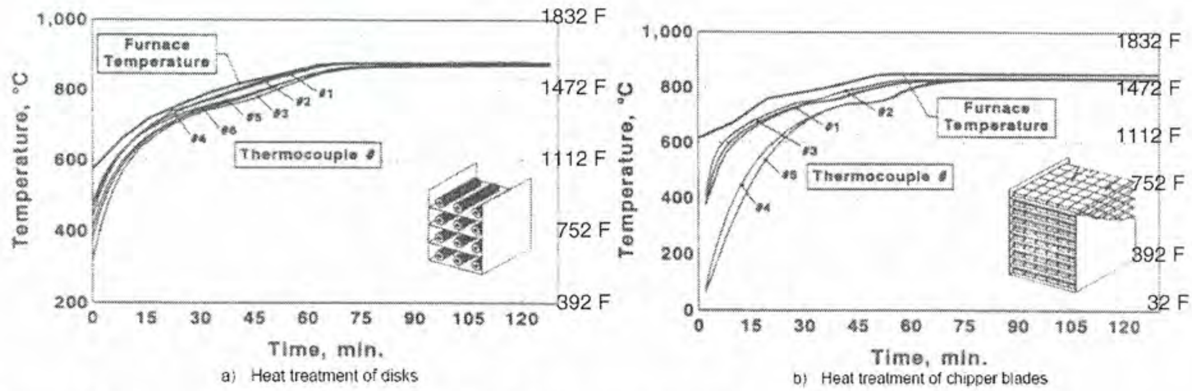


Figure 4 **Temperature response of loaded heat treatment furnace during austenitizing.**

Voigt[5,15,16,17] reported temperature variability in instrumented production loads in his studies. Voigt developed a heat treatment procedure qualification to compare the many variables for a successful heat treatment. The variables in heat treatment can be simplified to four key components upon which the rest have some relation. Table 2 lists the critical HTPQ variables from his research.

Table 2 Four key variables of heat treatment.

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

Load variability is not limited to heat treatment only. Styczynska[20] in 1996 documented the effect that packing had on a carbonitriding process. Using statistical process control, he determined the extent of inadequate treatment for the center of the load. With this knowledge, the company then improved the furnace design.

The influence of complex geometries and castings processed as batches not only influences the time to reach steady state but the temperature also. Every casting in the batch will have a different orientation to the heat source. Since the castings are heating non-uniformly, the steady state could be a range of temperatures depending on the uniformity of heat sources surrounding the casting. No amount of additional time will significantly improve the uniformity of the temperature distribution once the equilibrium state is reached.

The extent of non-uniformity is dependent on loading orientation, the heat source location, and part geometry. There are limited opportunities to optimize loading configurations since production quantities are small with similar sequencing occurring infrequently.

2.2.2 Austenite Formation

One of the main purposes of austenitizing heat treatment is to obtain sufficient austenite for hardening later in the cycle. Steps a-f in Figure 5 show the austenitizing process. As a critical temperature is reached, the ferrite (alpha) phase transforms into austenite starting at boundary areas. The transformation continues to grow and encompass all the ferrite and iron carbide. The transformation occurs rather quickly once above the critical temperature as shown in Figure 6.

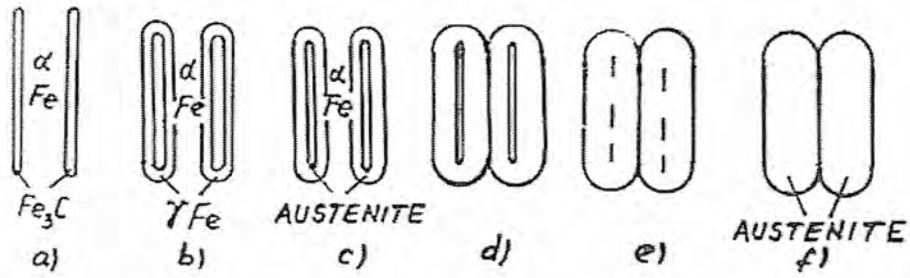


Figure 5 Transformation of a pearlitic structure to austenite when heating an unalloyed eutectoid steel of 0.8% C[2].

However, the time is dependent on the extent of heating above the critical temperature and the coarseness of the initial microstructure. Thin ferrite grain boundaries and larger surface area to volume ratios dissolve faster than blocky ferrite[7]. Another key consideration is austenite grain growth. At high temperatures, the grains of austenite continue to grow. When these are cooled, the larger austenite sizes translate into larger ferrite/pearlite/martensite sizes. Patterson[7] reported that no significant austenite grain growth occurred for low alloy steels held for 2.8 hours at 1900 F.

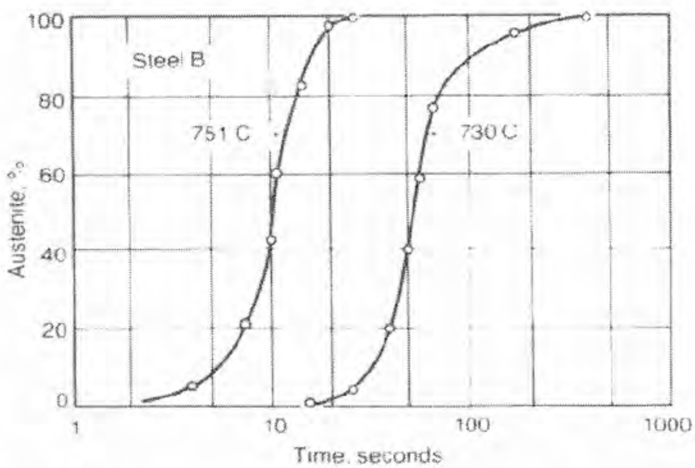


Figure 6 Effect of austenitizing temperature on the rate of austenite formation from pearlite in eutectoid steel[2,13].

2.2.3 Carbide Homogenization

Another central purpose of heat treatment is to homogenize carbides that have become segregated. As the austenite grows (Figure 5), the iron carbide begins to diffuse into the austenite. This occurs because carbon has a higher solubility in austenite than in ferrite. Calculations by Brooks[1] have shown that homogenization of carbides over the entire length of a casting is infeasible, but isolated homogenization of carbides across individual dendrites is possible during the course of a normal heat treatment cycle. Times and temperatures for austenite transformation and localized carbide diffusion is shown in Figure 7 for a fine pearlitic steel[1,2]. The curve on the left shows the beginning of the disappearance of pearlite, and the second curve shows the final disappearance of pearlite to 99.5% austenite. The third curve indicates the time and temperature to dissolve carbides, whereas the fourth curve is for the final disappearance of carbon concentration gradients.

Patterson and Bates[7] identified the time required for various grades of steels to complete both austenitization and localized carbide homogenization without degradation in mechanical properties. Table 3 summarizes their work. They noticed that the original microstructure plays a significant part in determining the time necessary for localized carbide homogenization. The fine microstructure of the manganese alloy required less than two minutes for carbide homogenization, whereas the other two coarse microstructure alloys took much longer. The thickness of cementite and ferrite influences the time because finer microstructures have smaller distances for the carbides to diffuse. Localized homogenization in pearlite is faster than ferrite because the carbon in pearlite is more evenly distributed[7]. When ferrite is present, the carbon from the surrounding cementite has to diffuse half the distance of the ferrite grain size. Large blocky ferrite requires longer time for carbon to diffuse[7].

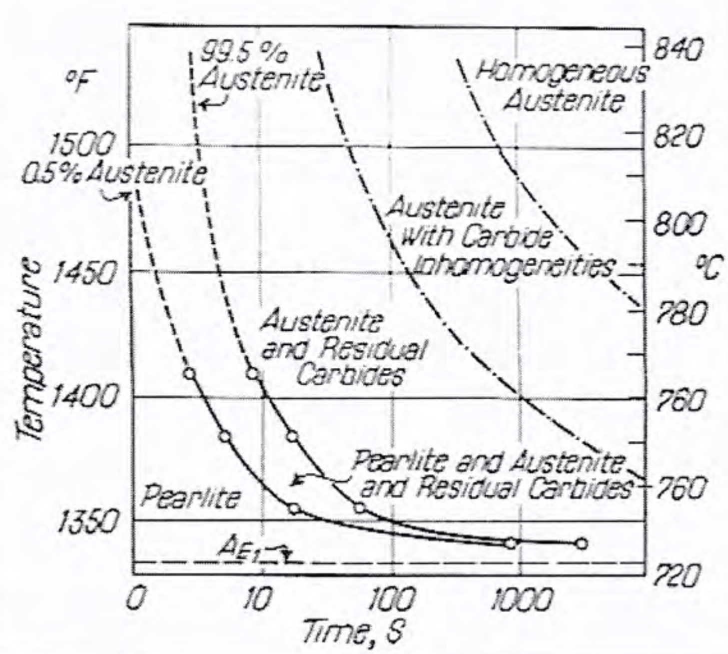


Figure 7 An isothermal TTT diagram showing the effect of austenitizing temperature and time on the formation of austenite from fine pearlite.

Table 3 Time required (minutes) versus temperature (°F) for complete austenitization of three alloys.

Temperature (°F)	Plain Carbon	1.3 Mn-0.25 Mo	2.4 Cr-0.95 Mo
1650	<17	2	17-30
1700	<17	<2	<17
1800	2	<2	2
1900	<2	<2	<2

Furthermore, the extent of diffusion is dependent on the alloy in question and the ramp up duration. Voigt[5,12] demonstrated that the extent of carbide diffusion is a function of time and temperature, and that shorter times at higher temperatures can replace longer times at lower temperatures. The key factor in determining the extent of diffusion is soaking temperature. Their data suggests that increasing the temperature by 100 F cuts the hold time in half for carbon to diffuse the same distance. Section size also affects the carbide homogenization time because heavier section sizes tend to have coarser microstructures than thinner sections. The coarser microstructures have larger ferrite sizes. Past research suggests that larger castings, which heat up slowly, may be closer to full transformation on reaching the final austenitization temperature[7].

2.3 Control Strategy

Based on the previous discussion, a basic understanding of what is occurring in the process can be determined by measuring time and temperature in the load. Current industry practices, however, employ a control strategy that is unrelated to the process strategy. The control strategy involves using thermocouples to measure the air enveloping the load. The temperature measured by the sensor may or may not be indicative of the load conditions. Comparing the temperature input to a user-defined set point controls the heat treatment operation. The controller's internal function (PID) then decides an appropriate output signal to control the heat input into the furnace. Once the set point temperature is reached, the controller then ensures it is maintained. The control strategy utilized by the industry is linked to how the controller responds to the furnace air temperature. Figure 8 shows a simple schematic of the furnace and the controller.

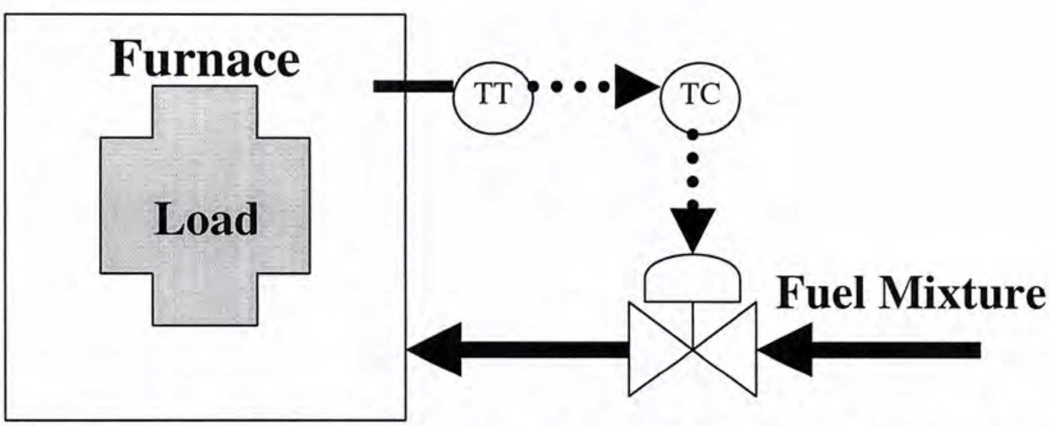


Figure 8 Schematic of the heat treatment control system (TT- temperature transmitter and TC-temperature controller).

In describing a heat treatment, the steel casting industry uses standard control terminology to describe what is occurring. **Ramp** is the time required by the controller to bring the control thermocouple to the set point temperature. Once ramp time is completed, the controller enters into its control **soak** phase as it maintains the input temperature equal to the set point. The use of **ramp** and **soak** in heat treatment provides no indication of the current load conditions; however, industry bases their rules of thumb on the control sensor's response. These rules are a natural result devised by industry to compensate for the shortcomings of the control strategy used. Figure 9 shows a typical control strategy for heat treat in the steel casting industry. Note that the load thermocouple from Figure 2 is included to demonstrate that process soak occurs in both the control ramp and control soak phases.

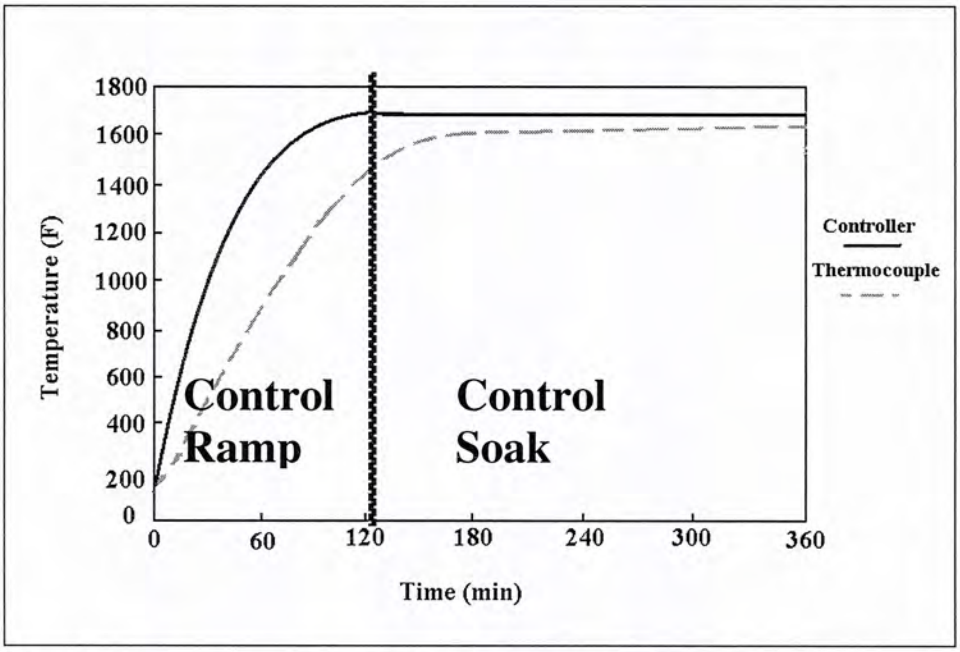


Figure 9 Time-temperature profile showing the ramp and soak phases of the control strategy.

3 Process and Control Strategy Disconnect

The problem with the control strategy employed is that the control thermocouple may not accurately indicate load conditions. Although ramp time is completed, the load is still increasing in temperature as part of its process soak phase. Since the time to complete process soak is unknown, industry specifies for its control strategy any time after ramp as soak. The times for soak is longer than necessary to account for the maximum amount of variability possible while still maintaining quality. Rules that work for one batch are then applied to all batches using a link such as largest section size.

The reasoning behind the '1-hour-per-inch' rule is to ensure adequate time to complete each phase in the process strategy and compensate for any load time/temperature variability. The problem with the rule is that it is based on two assumptions dealing with ramp and section size. The first of which is that the completion of ramp is a key transition point that acts as an equalizer for loads of different size, weight, and density. Once ramp is completed loads that have the same section size should behave similarly thereafter. The second is that a linear correlation exists between time and section size. Once soak begins, loads with larger section sizes require more time than those of smaller cross sections. In order to eliminate its continued usage, it must be demonstrated that the control strategy upon which it is based has no correlation to the process strategy.

Table 4 Experimental setups to investigate control and process strategy disconnect.

	Experiment A	**Experiment B**
Focus	Effect of Control Thermocouple Position on Ramp	Load Response After Ramp Completion
# of Loads	1	22
Current Measurement Strategy	1 Air Control Thermocouple	182 Load Thermocouples (2 - 6 per Load)
Furnace Size	10x10x3-ft Front-Loading Furnace	From a 15x11x11-ft Car Bottom Furnace To a 10x10x2-ft Front-Loading Furnace

To validate the disconnect between the process and control strategy, two experiments were designed using production loads in industry. Time and temperature profiles were taken from instrumented loads in addition to their controller temperature readings. The focus of Experiment A was to investigate the effect of the control thermocouple position, and Experiment B was to investigate the response of the load once ramp was completed.

3.1 *Experiment A- Ramp Variability*

For Experiment A, the purpose was to determine the effect and extent that the position of the control thermocouple has on the temperature measured and the control ramp time. A control thermocouple with the ability to change positions was used to control the heat input for a production load. It was not intended to change the heat input during the process, but to measure the variability in temperature at specific positions from the load. Large changes in temperature would indicate that ramp time is not linked to load conditions. The control thermocouple is referred to as the 'extendable thermocouple' in this portion of the paper.

3.1.1 Methodology

In this experiment, a 10x10x3-ft front-loading furnace with a 12-ton load (including trays) was heated using normal operating procedures. The control strategy for this load was a controlled ramp of 1000 °F/hr in order to prevent thermal stress and cracking. Holding time began when the control thermocouples reached 1750 °F. The control thermocouple was located near the center of the load suspended from the ceiling. The furnace also had three other air thermocouples located in the sides and back. For this trial, load thermocouples were placed in the center of L-shaped blocks (8x8x4-in with a 4" cube cutout), which were located in the lower corners and center of the load. A temperature measurement from the casting surface was taken near the extendable thermocouple.

The procedure for Experiment B was to move the extendable control thermocouple during ramp up when the burners were firing 100% for a load. The thermocouple was moved from the load surface (0") to the following heights: 1.5", 4.375", 7", 9.625", and 12.25". Then it was lowered again to the load surface, and the process was repeated. The thermocouple was moved at intervals of 2 minutes initially and then 4 minutes during later stages to ensure equilibration.

3.1.2 Results and Discussion

Figure 10 shows the air temperature measurements in the furnace for Experiment A. The four air temperature measurements are for the three locations surrounding the load and for the control thermocouple. The temperature readings of the other three thermocouples are independent of those from the control thermocouple until around 300 minutes. Thereafter, the control thermocouple influences the others because once the set point temperature is met or exceeded the controller adjusts the firing rate accordingly and the air temperature changes. An analysis of the controller thermocouple was performed by examining the correlation of temperature measured to its height from the load surface during 180 to 270 minutes. Cubic polynomials with a minimum Rsquare value of 0.97 were fit to each thermocouple height as shown in Figure 11. The temperature measurement of the adjacent load surface is included to verify the cubic fit. The curves follow the same trend indicating that a well-defined temperature gradient exists at any time during ramp.

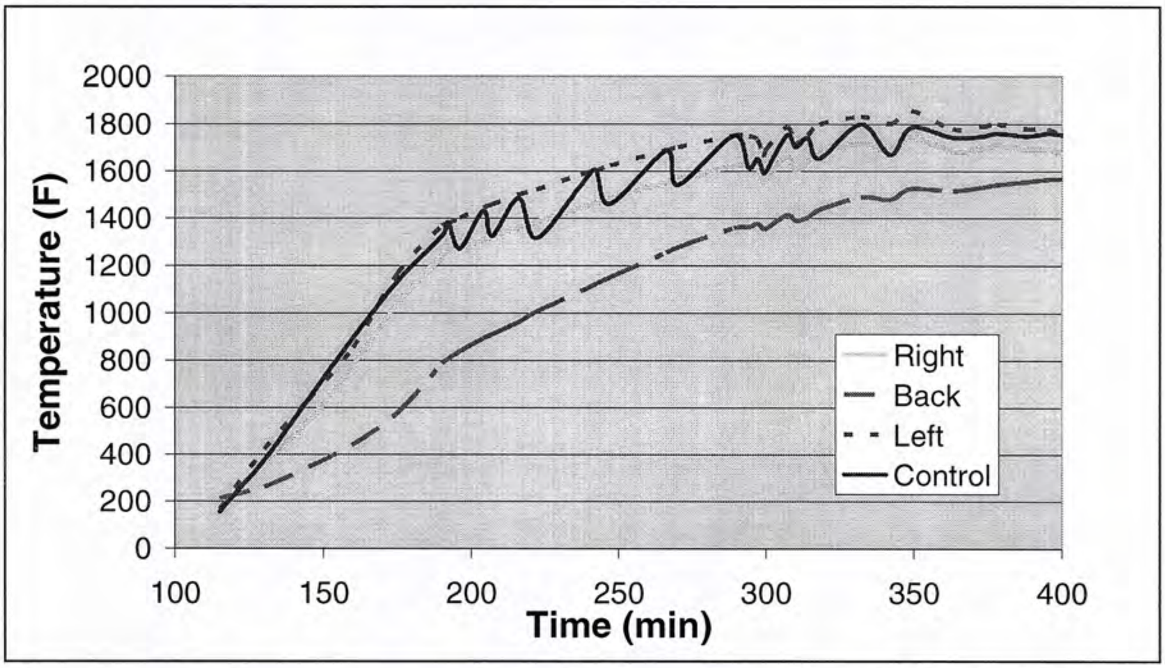


Figure 10 Furnace air temperatures enveloping a load's two sides and back of a front loaded furnace for Experiment A.

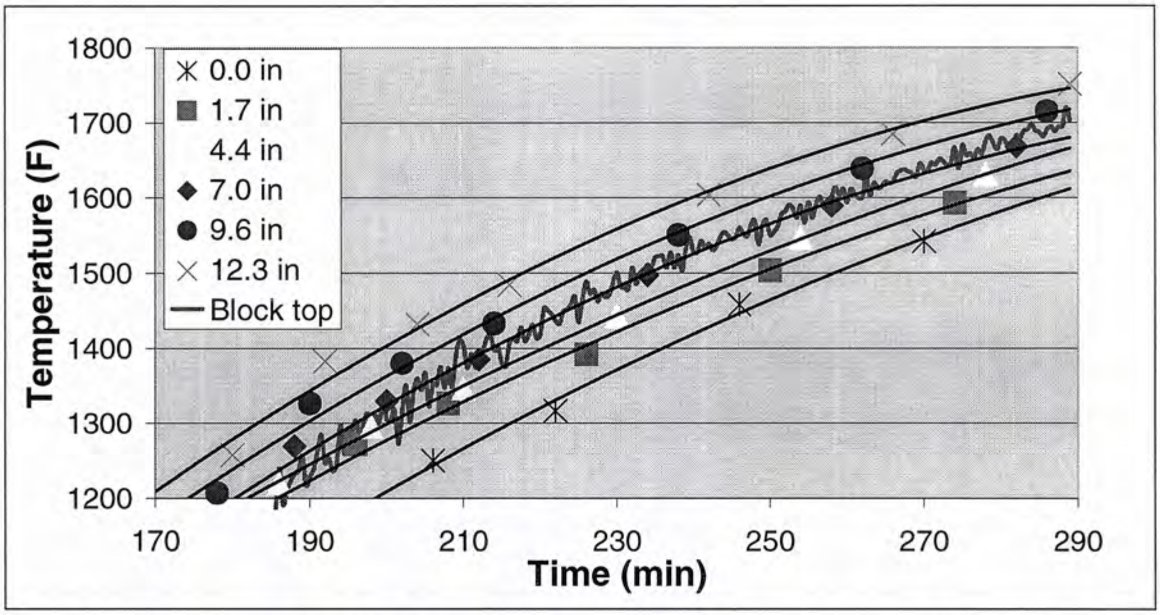


Figure 11 Correlation of height to temperature reading for the extendable control thermocouple in Experiment A. Cubic lines are fitted to the data points. The 'Block top' line is the surface readings from a casting in the vicinity.

With this information, generalizations can be made about the effect that location (height) of the control thermocouple has on the length of ramp time and the difference in temperature from the load surface that specific heights will have at any time during ramp. These effects are tabulated in Table 5. Ramp completion time is the estimated time for the controller thermocouple to have registered 1750 ˚F if the controller thermocouple had been left at that height for the process. The average temperature difference of the air is the temperature difference between the load surface and the average temperature (during time 170-290 minutes) at a particular height. For example, +184 ˚F at 12.25 inches means that this particular height was on average 184 ˚F hotter than the load surface at any point in time. Both the temperature difference from the load surface and the length of ramp time were found to be linear in relationship for the parameters measured.

Table 5 Experiment A: Effect that thermocouple height has on the total time to complete ramp up because of differences in air temperature at each height. The difference in temperature between the load surface and each measured height from 170 to 290 minutes was averaged and listed here.

Height from Load Surface (in)	Calculated Ramp Completion Time (min)	Average Air Temperature Difference (˚F)
12.3	290	+184
9.6	298	+141
7.0	307	+108
4.4	315	+79
1.7	323	+49
0.0	330	0

The interesting insight that this experiment reveals is that the position of the thermocouple to the load can influence the length of ramp. In this case, ramp would be lengthened an additional 40 minutes if the location of the control thermocouple had been moved from 12.25 inches above the load to the load surface. The time to complete ramp is not only affected by the load's size, weight, and density, but it is strongly dependent on the placement of the sensor to the load. A load that is accidentally placed near or touching the control thermocouple will have a different ramp time than one that is far away. The placement of the sensor is crucial to when the completion of ramp occurs because temperature changes depending on location to the burners and the load. The assumption that ramp completion acts as a unifier of loads is not valid. Once ramp is completed, it cannot be assumed that loads with the same section size will behave similarly thereafter.

3.2 Experiment B- Ramp and Soak Difference

To understand the response of the load once ramp is completed, time-temperature profiles were collected from four industrial partners for twenty-two instrumented heat treatment loads. The purpose of this experiment was to examine the variability in soak times after ramp completion for various section sizes in a load. Currently, conservative practices are designed to encompass all possible variation in temperature and time to reach that temperature; however, the rule assumes a relationship to section size. By examining the maximum amount of soak time needed for various section sizes from sample instrumented loads, the justification for these rules can be refuted.

3.2.1 Methodology

The data was collected from instrumented steel castings with various section sizes less than 8". In all, 174 thermocouple readings were compared to the response of their load control thermocouple. Once ramp time was completed, the time delays or times to reach specific temperatures above 1400 F were found. The data was provided by partners that employed unique heat treat procedures even though many of their alloys were similar. Each thermocouple measurement was normalized to the set point temperature of its load in order to compare loads that had set point temperatures ranging from 1625 to 1850 F. Furnace sizes ranged from a 15x11x11-ft car bottom furnace to a 10x10x2-ft front-loading furnace. The normalized temperatures were compared to time once ramp was completed.

3.2.2 Results and Discussion

The results are displayed in Figure 12. A time of zero indicates that the controller has reached the set point temperature, and ramp is completed. The interesting trend in the data is that 96% (168 out of 174 possible) of the thermocouple readings took two hours or less to reach at least 92% of the set point temperature. Those that took more than two hours occurred with loads that were packed denser than usual or placed in a furnace inadequately maintained. Furthermore, 85% (148 out of 174 possible) required one hour or less to reach 92% of the set point temperature after ramp has completed. The value of 92% was selected because this corresponds to a temperature of at least 1500 F for all measurements, which meets the minimum requirements for austenitization and carbide diffusion. The time required to increase the temperature thereafter dramatically increases signifying that the temperature is approaching equilibrium. No identifiable patterns were identified between section size and time to reach a percentage of the set point temperature as the 'hour-per-inch' rule uses. The variation in the data is a result of variables such as packing density, load size, and set point temperature. This suggests that the 'hour-per-inch' rule is too conservative in order to account for the other factors, or that four hours for a 4-inch section is longer than necessary for a qualified heat-treat load.

To confirm that the control strategy is too conservative, the time data in Figure 12 was normalized with the time designated by the 'hour-per-inch' rule for each section size. For example, the soak time for all 2" data was normalized over 2 hours or 120 minutes, and 3 hours for the 3" section size. Similar procedures were done for the others. The normalized temperature and normalized time data were compiled and tabulated as percentages of the total measurements that were less than fractions (25%, 50%, 75%, 100%, 150%, and 200%) of the time specified by the hour-per-inch rule in Table 6.

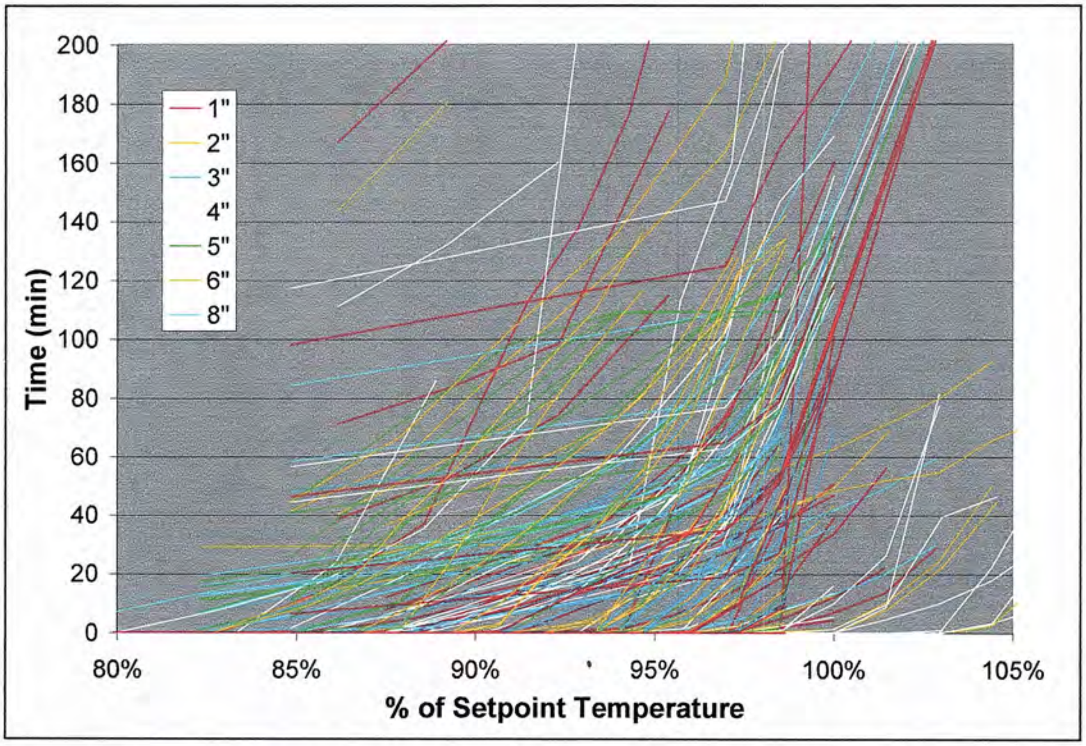


Figure 12 Instrumented load data comparing the time delay after completion of ramp to the % of the set point temperature.

Table 6 Percentage of trials which achieve a % of the set point temperature in a given fraction of the time prescribed by the hr/inch rule.

% of Set Point Temp	**# of Readings**	**Fraction of Hr/inch Rule Used**					
		25%	**50%**	**75%**	**100%**	**150%**	**200%**
85%	**174**	**93%**	97%	97%	98%	99%	99%
90%	**173**	**88%**	95%	97%	98%	99%	100%
*** 92%**	**173**	**82%**	**94%**	97%	98%	98%	99%
95%	**167**	**70%**	**91%**	96%	97%	98%	98%
100%	79	**41%**	**62%**	**78%**	**81%**	**89%**	95%
105%	28	**46%**	**57%**	**68%**	**75%**	**79%**	**79%**

* Temperature reading is equal or greater than 1500 F in each load.

The data exhibits the trend that as each thermocouple approaches the set point temperature, the fraction of the '1-hour-per-inch' rule used decreases along with the number of readings that reach that point. Specifically, only 79 out of 174 readings (45%) reached 100% of the set point temperature. Of those that did reach the set point temperature, only 81% were able to reach that temperature in less than the full time specified by the '1-hour-per-inch' rule. This suggests that it is infeasible to expect a load to actually reach the set point temperature. It would be more realistic for industry to expect the load to reach temperatures of 95% of the set point temperature, where 167 out of 174 readings (96%) did so. Using this expectation, 91% of the readings need ½ of the time specified.

Of interest to heat treat supervisors is determining if the load reached a sufficient temperature for austenitizing. The results show that 94% (162 out of 173 readings) required less than 50% of the soak time prescribed by the '1-hour-per-inch' rule to reach a minimum of 92% of the set point temperature. The data tabulated for trials that achieved 92% of the set point temperature was further separated by section size to investigate their contributions. Percentages of the total number of readings were found for fractions of the '1-hour-per-inch' rule as done previously. Similar separations could be done for other percentages of the set point temperature, but it is expected that similar results would be found. In general, measurements that used percentages greater than 50% of the '1-hour-per-inch' rule were limited to section sizes of 1" and 2" as seen in Table 7. The data suggests that there is no linear relationship in load soak time to section size as the standard suggests. The load temperature is function of many factors of which section size cannot accurately portray. Based on this result, the '1-hour-per-inch' rule might be an acceptable method to determine hold time for only very small section sizes.

Table 7 Percentage of trials which achieve 92% of the set point temperature in a given fraction of the time prescribed by the hr/inch rule.

Section Size (inch)	**# of Readings**	**Fraction of Hr/inch Rule Used**					
		25%	**50%**	**75%**	**100%**	**150%**	**200%**
1	**35**	**63%**	**83%**	**86%**	**89%**	**91%**	97%
2	**34**	**79%**	**91%**	97%	97%	97%	97%
3	**36**	97%	100%	100%	100%	100%	100%
4	**33**	**88%**	**94%**	100%	100%	100%	100%
5	**19**	**74%**	100%	100%	100%	100%	100%
8	**13**	100%	100%	100%	100%	100%	100%

Thus far the analysis has used normalized temperatures to enable comparison of loads that underwent varying heat treatment procedures. The purpose of a heat treatment is not to reach a certain percentage of the set point temperature but to ensure a minimum temperature is met. For this reason, many procedures call for higher than necessary temperatures just to ensure that the temperature requirements are met. Suppose that the criterion for this analysis was to increase the load temperature to 1500 F. The results from the data are presented in Table 8. Slights differences in the percentages to reach fractions of the '1-hour-per-inch' exist, but in general the trend is the same as that given in Table 7. The inclusion of this information may seem redundant; however, by using temperature instead of normalized temperature, the analysis can examine the effect that set point temperature has on soak time to 1500 F. Table 9 demonstrates that set point temperature has a significant impact on the soak time to reach 1500 F. As expected, loads with the lower set point temperature are more prone to use higher fractions of the '1-hour-per-inch' rule. It is probable that many temperature readings were above 1500 F before the controller reached the set point temperature.

Table 8 Percentage of trials which achieve 1500 F in a given fraction of the time prescribed by the hr/inch rule.

Section Size (inch)	**# of Readings**	**Fraction of Hr/inch Rule Used**					
		25%	**50%**	**75%**	**100%**	**150%**	**200%**
1	**35**	**71%**	**77%**	**86%**	**89%**	**91%**	97%
2	**34**	**94%**	**94%**	97%	97%	97%	97%
3	**36**	**94%**	100%	100%	100%	100%	100%
4	**33**	**91%**	**94%**	100%	100%	100%	100%
5	**19**	**84%**	100%	100%	100%	100%	100%
8	**13**	100%	100%	100%	100%	100%	100%

Table 9 Percentage of trials which achieve 1500 F in a given fraction of the time prescribed by the hr/inch rule and separated by the set point temperature for the load to which the reading belongs.

Set point Temp (F)	**# of Readings**	**Fraction of Hr/inch Rule Used**					
		25%	**50%**	**75%**	**100%**	**150%**	**200%**
1600-1700	**65**	**63%**	**80%**	**91%**	**92%**	95%	95%
1700-1800	**53**	100%	100%	100%	100%	100%	100%
1800-1900	**52**	100%	100%	100%	100%	100%	100%

3.3 Summary

The two experiments demonstrated that the assumptions for the control strategy are not valid. Ramp time is a function of the location of the load and burners to the control thermocouple. With ramp time being variable, the soak time assigned by the control strategy must account for it. The '1-hour-per-inch' rule must have a safety factor that encompasses the possibility that the control thermocouple reaches the set point temperature in a matter of minutes whereas the load could take hours. Industry has supposed that ramp time acts as equalizer for similar section size, when the data suggests that ramp time is an equalizer for all loads with section sizes less than 8". The majority required two hours or less to approach their steady state temperature, which is independent of section size. Industry cannot assume that the load will reach the set point temperature and that a linear relationship exists between section size and soak time needed.

4 Linking the Disconnect

A disconnect exists between the process strategy and the control strategy. The process strategy has two distinct phases: process soak and process hold. Process soak is the time required to bring the entire load to a steady state in temperature. Process hold is the time needed to satisfy chemistry distribution and microstructure requirements. The control strategy also has two phases: control ramp and control soak. Control ramp is the time required by the controller to bring the control thermocouple to the set point temperature. Control soak is the time the control thermocouple is maintained equal to the set point temperature. The process strategy requires knowledge of load conditions, whereas the control strategy is dependent on a relationship between a sensor and a heat input. The inability of the sensor to portray load conditions adequately is the cause of the disconnect; in fact, load conditions are oftentimes completely unknown. When ramp time ends for the control strategy, the process strategy is still in its soak phase as the load is still increasing in temperature. Long control soak times are assigned as a safety factor because the time for the load to reach a steady state temperature is unknown. The control strategy must be redefined to portray the process strategy if any production improvements are to be made.

4.1 Proposed Strategy to Link

The first task in improving heat treatment productivity and energy efficiency is to define clearly the function of the instrumentation. Instead of basing the control strategy on the sensors available as is done currently, the improved control strategy should specify its function based on the process strategy. The fundamental requirement for the process strategy is to identify when the load has finished soak. When comparing the two strategies, there are overlaps between their key phases. A possible improvement to the control strategy would be to blend them together as shown in Figure 13.

The improved control strategy will now contain the phases of control ramp, control soak, and control hold. Just as it is used now, control ramp will be completed once the control input has reached equilibrium with the set point value. The improvement will be measuring control soak. Control soak will be completed when the coldest location in the batch has reached a steady state. This would correspond to completion of process soak mentioned previously. The idea of coldest location is portrayed in the figure with multiple load thermocouple readings. Control hold, which relates to process hold, will be a decision variable based on the time needed for austenitization and homogenization. The purpose of defining the control strategy this way is to provide measurable phases during the course of a heat treatment. The key to this strategy is to identify correctly the transitions between phases. Currently, the soak to hold transition is the only phase that cannot be quantitatively measured.

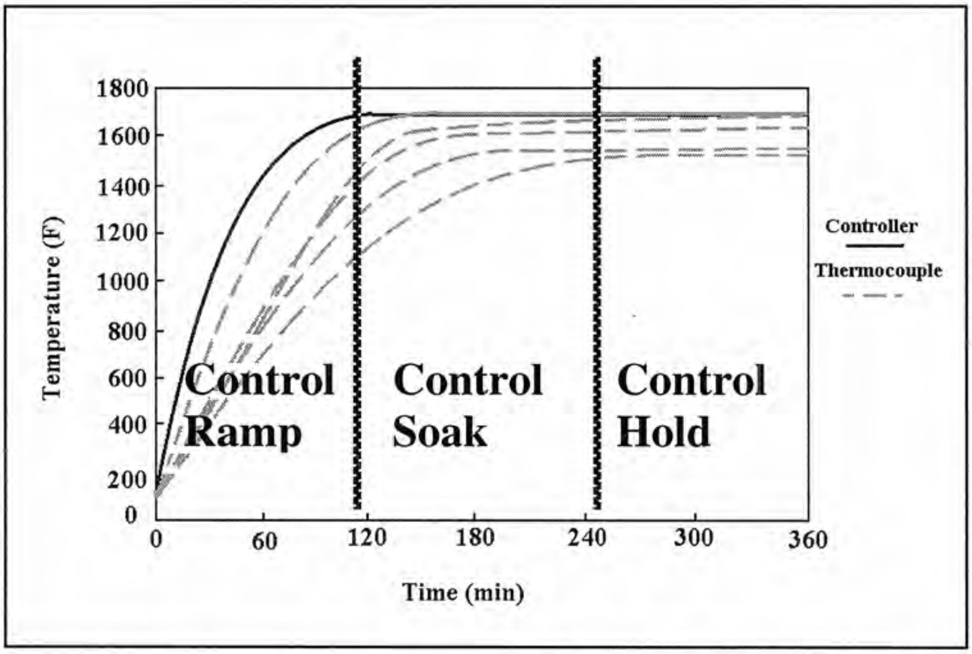


Figure 13 The improved control strategy showing the key phases of ramp, soak, and hold. Ramp is completed when the controller reaches temperature. Soak ends when the coldest load temperature reaches steady state.

4.2 Review on the Improved Control Strategy

No research has been found that focused specifically on control strategies for the heat treatment of steel casting production loads. As indicated before, detailed requirements for the process strategy have been developed, but the implementation of these ideas into the production batch environment has found little discussion. Instead, research has briefly mentioned possible solutions as a side note to the detailed process strategies. Patterson[7] suggested that a thermocouple should be embedded in the center of the thickest section of a block or casting to account for variable heating rates within a furnace and the associated lag time in the load. They concluded that austenitization treatment times should be measured from this location and not the exterior enveloping air.

Embedding a thermocouple in a casting would provide information on soak, but its practice has found limited application for many reasons. The task of loading the embedded thermocouple into the furnace, then replacing it for every load is labor intensive. Special care must be taken not to damage the wiring. Once the embedded thermocouple is placed properly with a load, the information it provides can only be used as an estimate. There is always the possibility that the temperature measured is not indicative of the conditions throughout the load. Another location might take longer to reach equilibrium or have a colder temperature.

The obstacle to correctly identifying the completion of soak is unknown variability in temperature and time. Heat treatment is a variable process in that temperatures change with time and are spatially dependent. Since uniformity is non-existent within the load, confidence in the ability of a sensor to describe load conditions is very low. The placement of multiple sensors would strengthen confidence; however, the addition of more thermocouples in the load is impractical. Because of the difficulty in setting up measurements, many foundries forego the direct measurements. What industry really needs is the ability to measure the entire load's temperature.

Industry understands the necessity of understanding the time-temperature profile for the entire load. Research has taken on the task of devising models that use heat transfer equations, thermophysical properties of the environment, and the properties of the steel parts to predict it. In 1994, Aronov[10] suggested that there was no reliable method to accurately predict heat up and soak times for heat-treating cycles that takes into account variations in furnace design, load arrangement and product mix. He then designed a mathematical model to predict soak times for simple geometries and loading practices. Although the solutions he found were still conservative because proper knowledge of the mechanism of heat transfer through the system's furnace and load were unknown, the results it provided were less than that the soak time using the '1-hour-per-inch' rule. He applied the model to six scenario loads and compared them to their assigned total soak time based on the '1-hour-per-inch' rule as shown in Table 10. Aronov[10] found that the thermal soak and metallurgical soak for whole load of 6 tests was less than the holding time needed by conservative rules.

Table 10 Thermal soak time data comparing conservative rule and model[10].

Test #	Load	Total Soak Time Assigned (min)	Thermal Soak Time from Model (min)*
1	Disks	60	10
2	Trunnions	120	73
3	Chipper Blades	60	17
4	Bolts	90	34
5	Shafts	90	83
6	Pins	330*	14

***Includes time for carburizing**

Since then, work at the Worcester Polytechnic Institute has continued to develop a loaded furnace temperature modeling and analysis program. In 2000, Lu[18] reported that they developed a model using very complex sets of heat transfer equations to solve problems for a single simple part in a furnace. By 2003, this model had been extended (Kang) to a computer system called Computerized Heat Treating Planning System for Batch Furnace (CHT-bf)[19]. The system optimizes thermal schedules and load patterns in batch processes and has the ability to work with random packing and arbitrary shapes unlike other systems developed.

These models, which have become more accurate as computing technology has advanced, face serious obstacles for widespread implementation in the steel casting industry. To setup the model, detailed information is needed concerning the furnace and the load. The industry in general knows very little about the process conditions of their furnace let alone its heating patterns. The accuracy of the model is only as good as the data entered into it. Secondly, the industry functions as a job shop with very complex geometries. Heat treat batches are assembled with parts that may not be repeated for months. The effort to develop models to simulate the load configuration that occurs infrequently is not justified. Essentially, the industry needs evidence from production loads to confirm the models, but few loads are produced consistently to validate them. What the industry needs is a control strategy that uses real-time measurements on the load conditions to determine the completion of soak.

4.3 Temperature and Energy Correlation

Measuring temperature is a difficult method to determine load conditions because it is spatially dependent and provides only sample data. Temperatures are variable within the load, and the number of sensors used to capture this information is inadequate. A better methodology would be to identify some way to measure the overall system to indirectly measure temperature. Examining the fundamentals of temperature might give additional insight.

Temperature is a measure of the average kinetic energy of molecules. It can be considered an energy density or an amount of kinetic energy contained by a mass of molecules in a system. The relationship that temperature has to energy is expressed by the following equation.

$$C_V = \frac{1}{m}\left(\frac{\partial U}{\partial T}\right)_V \qquad (1)$$

Where C_v is heat capacity at constant volume (kJ/(kg K)). T is temperature (K). U is the internal energy in a system (kJ). The m is the mass in the system (kg). It can be assumed that the heat capacity at constant pressure and volume is equal for a solid. The equation can be solved to the following.

$$dU = mCp(T)dT \qquad (2)$$

The equation shows that changes in internal energy results in changes in temperature based on a function of mass and the material's ability to store energy. The objective is to identify when soak time is completed or the load temperature is no longer changing. Of interest is when the rate of temperature change is approaching zero. The equation can be rewritten as the following.

$$\frac{dU}{dt} = \frac{mCp(T)dT}{dt} \rightarrow 0 \qquad (3)$$

Measuring the rate of energy change directly in the load is more difficult than measuring the rate of temperature change; however, if the furnace is viewed as a system, the energy input provided by the burners or the electric coils can be measured. The energy input into the load has a direct relationship to how the temperature or energy density is changing in the load. The load soaks up the heat energy and stores it, which increases the temperature of the load. The rate of energy into the system must equal the rate of energy stored by the load/furnace plus the rate of energy out as shown in equation (4). Notice that the rate of energy stored is equivalent to rate of internal energy change.

$$\dot{E}_{in} = \dot{E}_{out} + \dot{E}_{st} = \dot{E}_{out} + \frac{dU_{systen}}{dt} \qquad (4)$$

The E_{st} parameter depends on the rate of energy (i.e. temperature changes and phase changes) being stored by the load, air enveloping the load, and the furnace. When these have reached zero such that their temperatures are not changing without any phase changes, soak time has reached completion. When this occurs, the energy in will be equal to the energy out. Assuming that the energy out is constant, the energy in should be at steady state as shown in Figure 14. By measuring the energy introduced into the load, we can indirectly measure when the temperature is no longer changing in the load.

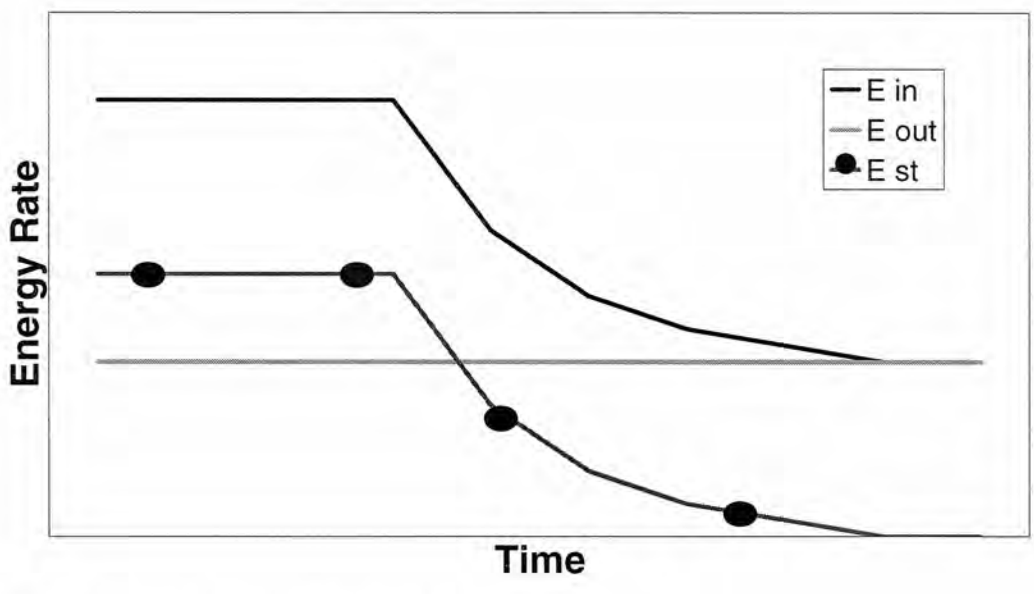


Figure 14 Example of expected energy rate changes.

4.4 Experiment C- Measuring Input Energy

An experiment was set up to tabulate energy usage with gas flow in a heat treatment production load. The experiment will be referred to as Experiment C to distinguish it from the others. For Experiment C, a trial was conducted to measure the energy usage for an annealing process with controlled heating and cooling. The 32x22x17-ft car bottom furnace with 68-ton load was heated using normal operating procedures. The furnace was divided into three control zones with controllers operating the burners in each respective zone. The control strategy for this annealing load was a controlled ramp of 100 °F/hr for 12 hours to 1650 °F and holding for 18 hours. Load thermocouples were placed in the center and surface of 15" (cube) blocks placed in the corners and center of the load. Figure 15 gives a sample of the temperature profile for this load.

Energy consumption was analyzed by identifying transitions in operations for the total gas usage, gas flow rate, and burner-firing rate, and then correlating them to transitions indicated by thermocouples. Figure 16 shows the rate of gas usage for the annealing process and the total gas usage. The total gas usage is equivalent to 409,500 ft^3. Three key times are identified in the graph: end ramp, end soak, and end hold. The gas consumed during ramp is used to heat the air to the set point temperature and partially heat the load. During control soak, the air is maintained at the set point temperature and the load temperature is increased until equilibrium is reached. The gas consumed during control hold is used to maintain the temperature of air and load. Table 11 lists the gas consumed during each phase of the heat-treat cycle and the percentage of the total gas consumed. Because this is an annealing process, the temperature of the load is decreased slowly over a period of time, which is designated as 'Cool'. The operation continues to consume gas because the furnace has energy losses during this time that decrease the air temperature faster than desired for the process. The natural gas used during cooling, however, is a small amount when compared to the other treatment sequences, hence the leveling off at the end for the total gas consumed in Figure 16.

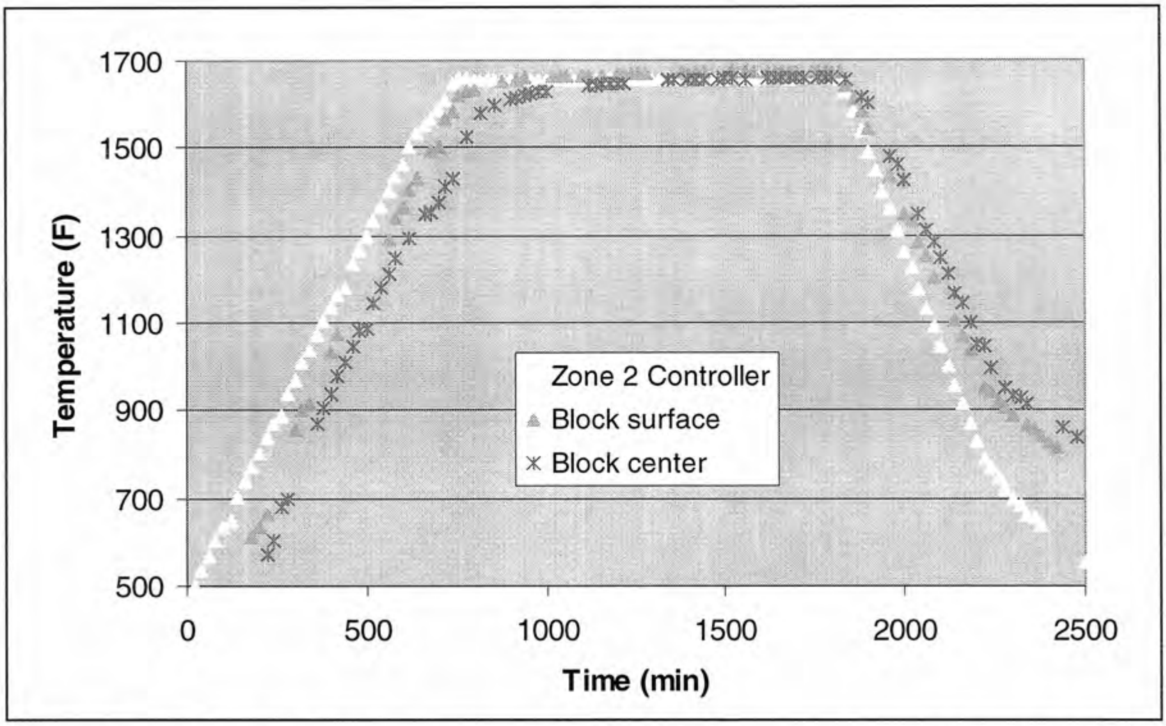


Figure 15 Experiment C time-temperature profile for the air thermocouple controller and a 15-in block in the center of the load in Zone 2 for an annealing process.

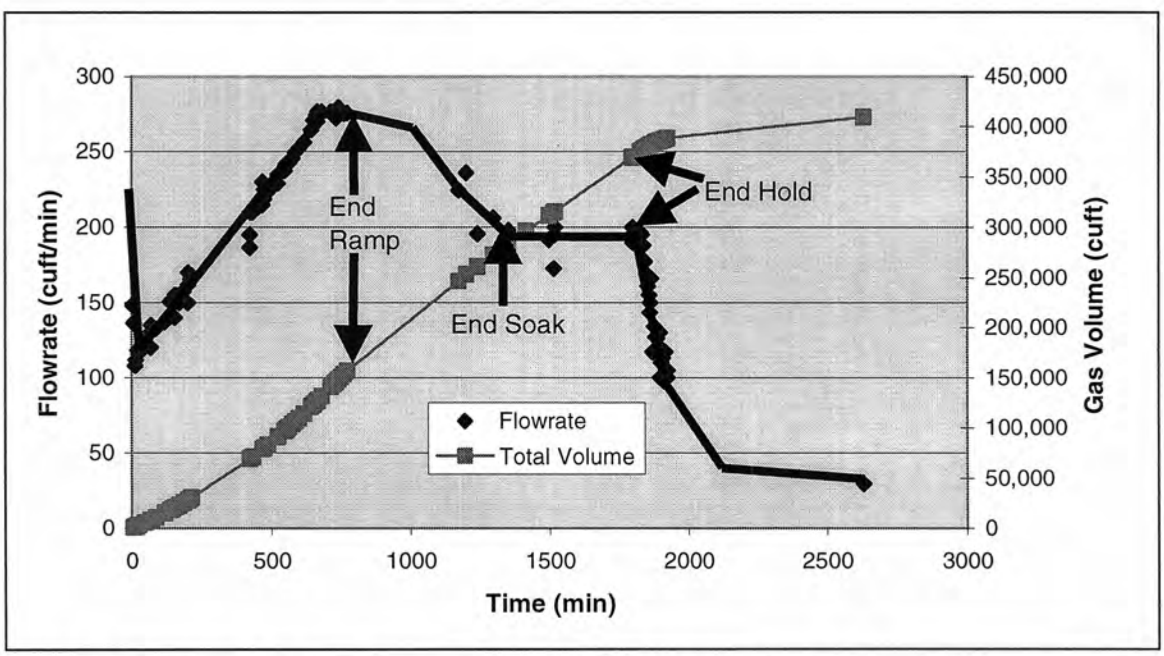


Figure 16 Experiment C, the gas usage rate with the total gas used during an annealing process with key transition points indicated. The final total gas used is equal to 409,500 ft^3, and the maximum flow rate is 280 ft^3.

Table 11 Gas consumed for various stages of heating cycle displayed in Figure 16.

Process Sequence	Time Period (min)	% of Time	Gas Consumed (ft^3)	% of Gas
Control Ramp	0 - 771	29%	156,775	38%
Control Soak	771 -1200	16%	96,385	24%
Control Hold	1200 - 1800	23%	116,585	29%
Cool	1800 – 2628	32%	39,755	10%

Comparing the data to the expected energy input, output, and storage model, a similar trend is seen. A decrease in the gas flow rate, which corresponds to the energy input rate, occurs after the completion of ramp. As the furnace/load reaches a steady state temperature, the gas flowrate levels off accordingly. From the data, soak ends at about 1200 minutes. Measurements from the instrumented load registered temperature increases after the end of soak to less than 10 F. The load temperature can be considered at steady state thus validating the claim that the equilibrium energy input corresponds to the end of soak.

Referring back to Section 2.2, the process strategy suggests that shorter times will suffice if the load is known to be at temperature. Using a 'what-if' scenario with the data collected, the potential savings in process time and energy consumption can be found. Assuming the load has minimal deviation from the set point temperature, one hour at temperature can theoretically be prescribed to the load with a sufficient safety factor. Control hold time is now reduced from 600 minutes to 60 minutes, and energy consumption is reduced from 116,585 to 11,678 ft^3. The overall potential savings are given in Table 12.

Table 12 Potential savings in time and energy by applying the improved control strategy proposed.

	Original Process	New Process	Savings	
			Value	Percent
Total Time (min)	2628	2089	539	20.5%
Gas Consumed (ft^3)	409,500	304,593	104,907	25.6%

Another piece of valuable information can be gathered by tracking input energy. Measuring the energy reveals the efficiency of the operation to deliver heat to the load. The most troubling trend exhibited from Table 11 and Figure 16 is that 29% of the total gas consumed was during hold; this is a considerable amount of gas just to maintain load temperature. Any energy input into the system during hold is not absorbed by the load, but lost from the furnace. The ~200 ft^3/min or 205,400 BTU/min (1 ft^3 = 1,027 BTU) were lost through wall losses, holes, flues, etc. The problem is that the gas rate during hold is 71% of the burners' maximum capacity of 280 ft^3/min, where an efficiency of 40-50% would be expected for a furnace of this size. This inefficiency translates into high gas consumption and subsequent cost.

Table 13 Experiment C, percentage of maximum flow rate used during holding period from Figure 16.

Gas Rate	Gas Flow (ft^3/min)	% of Max Flow
Pilot Light	18	6%
Max Capacity (100%)	280	100%
Hold	200	71%

4.5 Correlate Input Energy and Firing Rate

In Experiment C, a simple correlation was observed that could provide the industry with the same information as the gas flow equipment. This information is readily available to the industry for data collection and related directly to the controller. The controller controls the temperature by adjusting the flow rates of the fuel/air inputs. In many systems, this is called the burner-firing rate. There is a direct correlation between the burner firing rate control signal and the gas flow rate based on each valves' flow characteristics. A reasonable assumption is that the relationship is linear, as happened to be the case for Experiment C, which is shown in Figure 17.

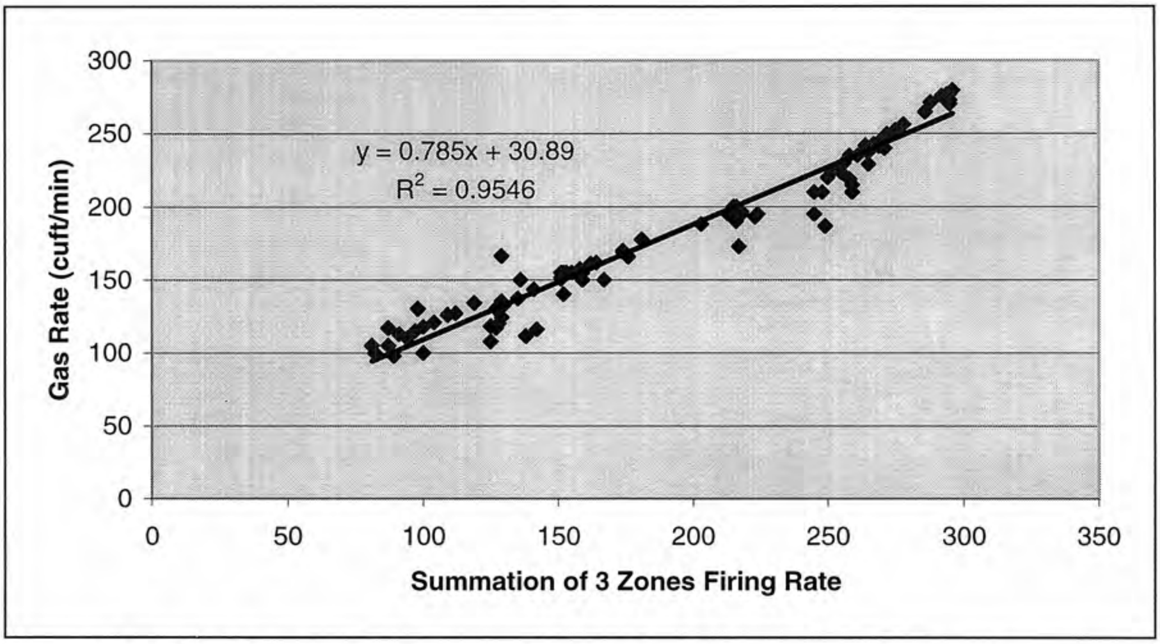


Figure 17 Relationship between firing rate and gas rate for the data collected for Experiment C.

The implications of this relationship is that once the flow rate has been correlated to firing rate, measurements of the firing rate can be used to track the efficiency of the process, estimate heating costs, and identify the end of soaking. Collecting this data should be simple since an electronic signal is used to transfer the valve open percentage to the controller. Even without the correlation to gas consumption, valuable information regarding how the load responds to the heat treatment can be seen just from the controller response.

5 Discussion Combined Strategy

5.1 Case Study- Firing Rate

Measuring the energy input or the output signal from the controller can serve as an indirect way to determine that load has ended its soak cycle. The strategy used to analyze the gas flow rate is applicable assuming that a linear relationship exists. To examine the potential method, a typical time temperature profile was provided from an industrial partner for a production load. Properties of the load and furnace were not provided, but they are unnecessary for the purposes of this example. In Figure 18, the lines represent individual thermocouple readings including one that serves as a control thermocouple. Additionally, another line is plotted that represents the output signal from the controller, oftentimes called firing rate by industry. As the furnace is heating up, the difference between control thermocouple and the set point temperature causes the controller to generate an output. The output signal directs heat input into the furnace.

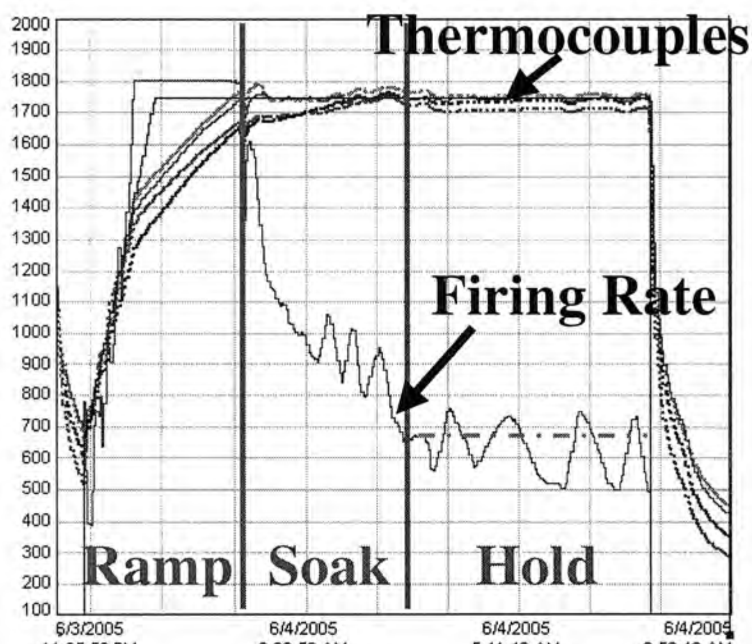


Figure 18 Time-temperature profile for a load that includes the normalized firing rate and the set point temperature. Temperature is in Fahrenheit.

Analyzing the firing rate can provide information on ramp, soak, and hold. Examining the ramp phase, the firing rate increases then plateaus. The cause for the increase and subsequent plateau is from a linear ramp strategy that was used to heat up the load. The set point temperature was slowly increased until a final value. The firing rate signal maintained the linear increase in furnace temperature, which resulted in the firing rate increasing linearly itself until it reached its maximum. Thereafter, the heat input could not supply sufficient energy to keep the furnace temperature heating linearly. At this point, the burners operate fully at 100% just like an uncontrolled ramp.

Once the furnace air temperature reaches the set point temperature, the ramp phase is finished. The controller's function now is to maintain the air temperature by adjusting the firing rate. Although the controller temperature is at steady state, the load is still increasing in temperature as it soaks up energy. This is reflected by the firing rate, which doesn't drop down instantly to an equilibrium value. The firing rate slowly decreases over time to a steady state value around which it oscillates. The time required to reach that point is directly linked to the load reaching its steady state temperature. Once reached, soak time has ended, and hold time begins.

At this stage, the firing rate has balanced the energy input to energy losses. The firing rate can be used to understand the fuel efficiency of the operation and the total amount of energy used. Once at the steady state, a high firing rate value indicates low furnace efficiency meaning that a significant amount of energy is lost. Increasing the energy efficiency will result in lower firing rate values at equilibrium. The other correlation is that the total area under the firing rate curve corresponds to the total energy used during the process. By separating the area into those portions that pertain to ramp, soak, and hold, the percentage of energy used by each can be determined.

5.2 Firing Rate Analysis

The data provided in Figure 18 was analyzed to determine the amount of time and percentage of energy used. Additionally, the time and energy used were found if the improved control strategy had been implemented in a 'what-if' scenario and listed as **New Total.** For this example, it is assumed that 60 minutes are needed for hold time as a default value. During the hold cycle, the load had a maximum temperature range of 1706 to 1771

°F. The results are listed in Table 14. The improved strategy is broken down into ramp, soak, and hold to demonstrate the contribution each phase has to the time and energy used. Note that the values for ramp and soak would be equal under the old strategy to the new. All savings in time and energy are because hold time has been reduced.

Table 14 Potential time and energy savings by using firing rate to identify soak.

Process Sequence	Time Period (min)	% of Data Process Time	Gas Volume Used (cuft)	% of Data Energy
Data Total	**0-527**	**100%**	**8055**	**100%**
New Total	**0-360**	**68%**	**6388**	**79%**
Ramp	*0-136*	*26%*	3123	*39%*
Soak	*136-298*	*31%*	2666	*33%*
Hold	*298-360*	*11%*	599	*8%*

According to the improved control strategy, 298 minutes from the start of treatment were needed before the burners approached their equilibrium-firing rate of 36%. At this time, the load temperature has reached equilibrium, and the load is not soaking up energy. The improved control strategy suggests that the total process time for this particular load could be reduced to 68% of the actual process time, and energy consumption would be 79%. Although process time and energy use savings will vary between loads, furnaces, and companies, the data is indicative of the potential that is available with the elimination of the conservative practice. The key is identifying when the load is no longer soaking up energy and increasing in temperature.

5.3 Effect on Production

Implementing the improved control strategy to all heat treatment processes at a facility will lead to increased productivity and efficient usage of energy. An estimate of the yearly savings in production is possible from the data analyzed thus far if we assume that the firing rate analyzed in this section characterizes the average production in this furnace. Assuming the furnace operates 24 hours a day 7 days a week for 50 weeks, the company would heat-treat the following number of loads as shown in Table 15. Additionally, the approximate number of days to process 900 loads is given.

Table 15 Estimated number of loads processed in heat treatment for one furnace after one year and number of days to heat-treat 900 loads for the current and improved control strategy.

	Data Total	New Total	% Change
Loads/year	956	1400	+46%
# of Days to Heat Treat 900 Loads	344	235	-32%

During the past few years, surges in natural gas prices have heightened interest in energy efficiency. The gas industry has seen prices double during that time as shown in Table 16, and the future is uncertain. Currently the price is around $7 per thousand cubic foot, but the price is highly variability from day to day. The improved control strategy would enable companies to deliver the energy for heat treatment more effectively thereby reducing unnecessary gas consumption.

Table 16 United States natural gas industrial average price[21] (dollars per thousand cubic feet) listed for each month during 2001 to 2005.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	8.84	7.21	6.30	6.08	5.46	4.75	4.10	3.99	3.50	3.18	3.88	3.69
2002	4.05	3.70	3.78	3.64	4.07	3.86	3.80	3.62	3.89	4.18	4.72	4.92
2003	5.65	6.40	8.27	5.96	5.78	6.59	5.69	5.28	5.32	4.93	5.19	5.90
2004	6.76	6.56	6.01	6.09	6.37	6.86	6.44	6.38	5.70	6.05	7.66	7.57
2005	6.97	7.07	7.04	7.62	7.09	6.84	7.34	7.90	10.09	11.88	11.92	10.90

The potential yearly gas costs were found using the same assumptions mentioned previously and a cost estimate of $7 per thousand cubic feet and $10 per thousand cubic feet. The results are tabulated in Table 17. The yearly gas cost is shown for two scenarios: one where the furnace is operated at maximum production during the year and the other where an equal number of loads are processed. Even though the gas cost is higher at maximum production for **New Total,** 444 more loads were processed in the meantime. Additionally, it must be considered that this is the gas cost for one furnace. Generally, the costs and potential savings listed here would be multiplied by the number of furnaces that the particular company has.

Table 17 Potential savings total natural gas cost to heat load with improved control strategy for two gas prices.

		Data Total	New Total	Data Total	New Total
Gas Price ($/1000 cubic feet)		$7	$7	$10	$10
Gas Cost/Load		$56.38	$44.72	$80.54	$63.89
Maximum Production	Loads/Year	956	1400	956	1400
	Gas Cost/Year	$53,900	$62,600	$77,000	$89,400
Equal Production	# of Days to Heat Treat 900 Loads	344	235	344	235
	Gas Cost/Year	$50,700	$40,248	$72,500	$57,500

5.4 Discussion on Ramp, Soak, and Hold

Experiment A investigated the effect and extent that the position of the control thermocouple has on the temperature measured and the control ramp time. If ramp time is highly variable as this experiment demonstrated, then the industry must address the issue of whether longer or shorter control ramp times are more desirable. Shorter ramp times would be only beneficial for the current conservative practices because they have large safety factors assigned to soak time. The safety factor would compensate for the increased disparity in time between the control thermocouple and the load to reach their steady state. The shorter ramp times, however, would be detrimental to the improved control strategy because the control soak time would be lengthened significantly.

On the other hand, longer ramp times would reflect load conditions more closely. This would be beneficial if the improved control strategy were used. Recent research suggests that longer control ramp time results in shorter control soak time[22]. The relationship between ramp time and soak time can be easily explained by the firing rate. Longer ramp times mean that the firing rate is operating at higher rates longer. The subsequent effect on soak time is that the firing rate will decrease more quickly to the equilibrium value. If this were used in conjunction with the improved control strategy, then heat-treat times could be reduced even further.

Experiment B investigated the time delay for locations in the load to reach a percentage of the set point temperature. Measuring the soak time with thermocouples can not match the ability of the firing rate to ensure all locations in the load have reach steady state. One important piece of information that the firing rate does not provide is the load's temperature.

The data from Experiment B is very insightful in this aspect; 96% (167 out of 174) of the temperature readings reached at least 95% of the set point temperature. Only 45% (79 out of 174) of the temperature readings reached the set point temperature. This suggests that when the firing rate indicates the end of soak, the temperature of the load can be reasonably estimated to be about 95% of the set point temperature. Once soak time is completed, then a quantitative method can be used to determine the length of hold time. The hold time is dependent on temperature, which can either be derived from the coldest equilibrium temperature in the load or 95% of the set point temperature as shown by Experiment B.

There are many unanswered questions about firing rate requiring additional investigation. They include how effective is firing rate in providing real time feedback on load conditions. For instance, will an isolated heavy section with relatively small mass when compared to the load reach its equilibrium temperature after firing rate indicates equilibrium is reached? How do different section sizes and loads with varying temperature uniformities respond in comparison to the firing rate? Additional research to find correlations between temperature uniformity, firing rate, and soak time plus validate the improved control strategy is needed.

6 Conclusions

Batch heat treatments are variable processes in that the temperatures change with time and are spatially dependent. Time and temperature are critical to ensure a quality heat treat. Current control strategies employed by the steel casting industry are unable to optimize the requirements of the process. They are not specifically designed to address the variability issues caused by loading practices, load sizes, equipment design and maintenance, and material properties. To prevent degradation in quality, conservative standards for time and temperature are applied to all batches (hour-per-inch), which results in productivity losses and inefficient energy usage. The industry would be better served to define a control strategy that measures how the load responds to the treatment (soak) and modify hold time accordingly. Reductions in process and energy use by 30% are expected if the industry can correctly identify the completion of soak. Identifying soak time indirectly through the controller output signal has been shown to be a viable option.

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