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FINAL REPORT**CONTINUOUS AUSTEMPERING FLUIDIZED BED FURNACE****Principal Investigator:**

Dr. Malur N. Srinivasan
Department of Mechanical Engineering
Lamar University
Beaumont, TX 77710

Principal Subcontractor:

Kemp Development Corporation
P.O. Box 218943
Houston, TX 77218

Industrial Collaborator:

Quality Electric Steel Castings, Inc.
252 McCarty Drive
Houston, TX 77029

Respectfully submitted to:

U.S. Department of Energy
Idaho Operations Office
850 Energy Drive
Idaho Falls, Idaho 83401

By

Texas Engineering Experiment Station
Contracts and Grants Division
College Station, TX 77843-3000

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CONTINUOUS AUSTEMPERING FLUIDIZED BED FURNACE**Grant No. DE-FG07-94ID13323 Amendment M003****FINAL REPORT****SUMMARY OF PLANNED OBJECTIVES AND ACTUAL WORK PERFORMED:**

The intended objective of project was to show the benefits of using a fluidized bed furnace for austenitizing and austempering of steel castings in a continuous manner. This project was sponsored by the Office of Industrial Technologies of the Department of Energy and was awarded jointly to Texas A&M University at College Station (administered by the Texas Engineering Experiment Station), Kemp Development Corporation, Houston and Quality Electric Steel, Inc., Houston. For administrative purposes, Texas A&M University was named as the principal investigator, Kemp Development Corporation as the sub contractor to Texas A&M University and Quality Electric Steel as the industrial collaborator. The division of responsibilities was as follows:

1. Design of the fluidized bed furnace : Kemp Development Corporation
2. Fabrication of the fluidized bed furnace: Quality Electric Steel, Inc.
3. Procedure for austempering of steel castings, analysis of the results after austempering: Texas A&M University (Texas Engineering Experiment Station).

The Department of Energy provided funding to Texas A&M University and Kemp Development Corporation. The responsibility of Quality Electric Steel was to fabricate the fluidized bed, make test castings and perform austempering of the steel castings in the fluidized bed, at their own expense.

The project goals had to be reviewed several times due to financial constraints and technical difficulties encountered during the course of the project. The modifications made and the associated events are listed in the chronological order as follows:

1. After considering the estimated cost of the conveyor system as determined by Kemp Development Corporation, it was decided by Quality Electric Steel that it would be appropriate to first fabricate the fluidized bed furnace chambers and perform material handling manually rather than with a conveyor system. Once the austempering practice was established with the fluidized bed, the conveyor system could be added. As such, Kemp Development Corporation did not pursue the plans for the fabrication and installation of the conveyor system after this decision by Quality Electric Steel. The designs for the fluidized bed chambers for austenitizing and austempering were given by Kemp Development Corporation to Quality Electric Steel, who got the chambers fabricated at their own cost.
2. During the course of initial trials on the austenitizing chamber, it was found by Quality Electric Steel that the maximum temperature that could be attained in the chamber was only about 1400 F. Since the temperature required for austenitizing was 1650 F, it was clear that austenitizing of steel castings could not be done in this chamber. A meeting attended by Dr. Malur Srinivasan (Texas A&M University), Mr. Bill Kemp (Kemp Development Corporation), Mr. Ron Ledbetter (Quality

Electric Steel) and the fabricator of the chamber (subcontracted by Quality Electric steel) at the premises of Quality Electric Steel to resolve this problem resulted in the following modifications. The austenitizing chamber fabricated by Quality Electric Steel would be used for austempering instead of austenitizing, since the maximum temperature attainable (1400 F) was adequate for austempering. For austenitizing, a smaller fluidized bed available at Kemp Development Corporation would be used for further work. Since the austenitizing and the austempering are required to be done in quick succession, the fluidized bed at Quality Electric Steel would be moved to the premises of Kemp Development Corporation. Kemp Development Corporation would then perform the austenitizing and austempering treatments at a charge of \$300 per sample.

3. When the fluidized bed chamber was transferred from Quality Electric Steel to Kemp Development Corporation, one of the engineers at Kemp Development Corporation felt that the maximum temperature attainable was only 1400 F because of a flaw in the wiring connection treatment of the heating elements. He changed the connection with intent to draw more power from the mains and thereby increase the maximum attainable temperature. However, when trials were made with the new connection, the as the temperature attained being higher than before, the chamber (retort) flat sides bulged outward and made contact with the heater panels and shorted them. Thus this furnace could not be used any further as a fluidized bed, but just as a furnace with a stationary bed serving as the support for the castings. The project plan was therefore again modified to austenitize in this (now stationary) furnace and then use the already available and operable fluidized bed at Kemp Development Corporation for austempering.

4. By this time the termination date of the project (which had been extended twice before) was approaching and there were severe financial and other constraints to resolve the problems with the fluidized bed fabricated at Quality Electric Steel. As such the project plan had to be modified to subject only block one (instead of eight as planned earlier) to the austempering procedure and study the microstructure and mechanical properties of the block. The project concluded after the microstructure and mechanical properties were examined.

PROJECT DETAILS

Significance of Austempering of Steel in Fluidized Bed:

Austempering of steel is its isothermal transformation at a temperature below that for pearlite transformation and above that for martensite formation, so that the microstructure consists of bainite. Austempering offers several potential advantages such as increased ductility, strength and toughness at a given hardness and, reduced distortion of the product during heat. The major steps in austempering are austenitizing, quenching to the austempering temperature and isothermal transformation to bainite at this temperature. The austenitizing temperature ranges from 1450 F to 1675 F and the austempering temperature is usually in the range of 500 F to 750 F. The most common equipment for the austempering temperature treatment is the salt bath. However, fluidized bed furnaces have been used for austempering small lots of highly alloyed steels such as tool bits, gun components and complex castings. The advantages of the fluidized bed include the use of nontoxic mediums, flexibility to have controlled heating and cooling rates in a chosen window over a wide range of temperatures and others. It appears therefore appropriate to examine the feasibility of extending the use of fluidized bed austempering to low alloy steel parts as well. Furthermore, for continuous austempering, a fluidized bed may be considered to be a better medium than a salt bath, whose heat transfer coefficients can be irregularly affected by the superposition of the disturbance due to the motion of the parts in the molten salt bath.

Design of the Fluidized Bed:

In Fig. 1 is shown a schematic diagram of the continuous austempering equipment as originally designed by the Kemp Development Corporation. In this concept, the castings hang from a conveyor on racks approximately 18" square. The conveyor moves the castings approximately 2 feet (vertical) at one time. A piston and ratch assembly provides the 2 feet stroke. The casting has to pass rapidly from the austenitizing chamber to the austempering chamber and therefore, at the section between the exit of the austenitizing chamber and the entry to the austempering chamber, override cylinders are provided to lift the casting clear of the bed in the austenitizing chamber, push it rapidly forward for about 4 feet and lower the casting into the austempering chamber. The lifting, forward movement and lowering operations take place in about 5 seconds, to minimize air cooling of the casting and also to minimize the time in which the casting is out of contact with the medium. The furnace chambers are long, narrow and rectangular in cross section. The retorts in the furnace chamber are made of sheet steel with a thin wall so that it heats uniformly and cannot warp. This thin sheet is welded to a rigid carrier at the top and a rigid fluidizing frame at the bottom.

As in the summary, the conveyor system was not built and incorporated into the fluidized beds fabricated at Quality Electric Steel. The retorts of fluidized beds were made of 0.037" thick steel. The heater panels of this furnace were mounted about 1" away from the outside of the retort.

Design of Test Castings and Test Variables:

This task was performed by Dr. Malur N. Srinivasan, formerly of Texas A&M University and employed by Lamar University at Beaumont at present.

Test Castings:

Steel Composition:

After detailed discussions with the technical management personnel of Quality Electric Steel, the composition chosen for the steel to be austempered was as noted below. The considerations included austempering response and the needs of Quality Electric Steel.

Carbon: 0.25%, Manganese: 0.9%, Silicon: 0.5%, Phosphorus: 0.03% max, Sulfur: 0.025 max, Nickel: 0.45%, Chromium: 0.7%, Molybdenum: 0.2%, Vanadium, Aluminum, Titanium, Copper, Niobium, Zinc: traces. This corresponds to ASTM A 487 Grade 4, that is widely used by Quality Electric Steel.

Test Bar Design:

The main consideration here was to evaluate the response of bars of different thickness to the austempering variables. A detailed sketch of the test bar block is shown in Fig. 2. Four test bars of thickness: 0.5 inch, 0.75 inch, 1.0 inch and 1.5 inch were connected through a block which also served partly as a riser. With this design, it was possible to ensure that each bar in the block, being from the same heat, had nearly identical casting conditions.

Design of Experiments:

Assuming that the austenitizing treatment is properly done, the three important variables that affect the properties after austempering are: the austempering temperature, the austempering time and the casting size (thickness). It is now well established that the statistical design of experiments is one of the best methods to evaluate effect of the multi-variables with a minimum number of trials. Accordingly it was decided to study the effect of these three variables using a 2^3 matrix, with two replications. The designed experimental plan was as follows:

Table 1 - Statistical Design of Experiments

Serial Number	Austempering Temp	Austempering Time	Casting Thickness
1	+	+	+
2	+	+	-
3	+	-	+
4	+	-	-
5	-	+	+
6	-	+	-
7	-	-	+
8	-	-	-

Notes: + is the upper level of each variable
- is the lower level of each variable

Table 2- Upper and Lower Levels of the Variables

Variable	Upper Level (+)	Lower Level (-)
Casting Thickness	0.5 inch.	1.5 inch
Austempering Temp	350 C	450 C
Austempering Time	2 hr	4 hr

Austenitizing and Austempering Furnaces:

The original plan was to suspend the top hooks of the casting blocks from the conveyor system designed by Kemp Development Corporation and move the blocks at speeds corresponding to the chosen austempering time. This plan had to be replaced by manual loading, holding and unloading for reasons already detailed in the summary. It was decided to austemper the entire casting block instead of bars cut from the block, to ensure that each bar was subjected to uniform furnace treatment, particularly since manual handling was involved. However, studies on the effect of austempering would be restricted only to the bars cut from the block after austempering and the riser block would be excluded. The function of the latter was mainly to act as a common support for the bars of different thickness during austempering. The purpose of adding the bars of 0.75 inch and 1.0 inch thick bars to the block, though only the upper (1.5 inch) and the lower (0.5 inch) levels were needed in the experimental matrix was to serve as checks for the predictions based on the upper and lower level examinations.

RESULTS AND DISCUSSION:

As explained in the summary, it was possible to subject only one casting block to an austempering treatment. For this purpose, the casting block was austenitized at about 1650 F for 2.5 hr in the furnace fabricated by Quality Electric Steel, with the sand bath being stationary. It was then quickly moved to the austempering fluidized bed furnace available at Kemp Development Corporation whose temperature varied in the range of 835 F to 774 F during the period the block was being quenched in the furnace. In Fig. 3 are shown the details of temperature variation with time on the casting block surface and in the fluidized bed furnace. The top curve refers to the temperature variation on the surface of the cast steel block and the bottom curve to the temperature variation in the austempering fluidized bed furnace available at Kemp Development Corporation.

The four bars in the block were cut away after the heat treatment and were machined into test bars for tensile testing and impact testing. Pieces cut from each bar were also polished using standard metallographic procedures. All these tasks were performed in a reputed laboratory specializing in the needs of the foundry industry. The results of the laboratory tests are summarized in Table 4 to Table 6. For comparative purposes, the results obtained from a cast block that was directly cooled in air (normalized) from 1650 F are shown in Table 5 and Table 6.

Table 4 - Tensile Test Results on "Austempered" Bars

Lab ID No	Size, in	Area, sq.in	Yield strength, psi	Tensile strength, psi	%Elong. 2 in. gage	% Reduct. of area	Brinell hardness
1.5 in. keel bar 663-1	0.505	0.200	65,500	106,500	20.5	37.5	229
1 in. keel bar 663-2	0.505	0.200	64,100	101,900	21.5	40.5	NA
0.75 in. keel bar 663-3	0.505	0.200	63,900	101,900	22.0	44.0	NA
0.5 in. keel bar 663-4	0.357	0.100	63,000	104,800	23.0	43.0	NA

*0.2% offset method

Table 5 - Tensile Test Results on Normalized Bars

Lab ID No.	Size, in	Area, sq.in.	Yield strength psi	Tensile strength psi	%Elong. 2 in. gage	% Reduct. of area	Brinell Hardness
1.5 in. keel bar 664-1	0.505	0.200	59,800	97,400	24.0	48.5	197
1 in. keel bar 664-2	0.505	0.200	61,200	97,600	23.5	48.5	NA
0.75 in. keel bar 664-3	0.505	0.200	60,800	99,400	24.5	44.5	NA
0.5 in. keel bar 664-4	0.357	0.100	60,000	101,200	23.5	44.5	NA

Table 6 - Charpy Impact Test Results

Sample	Sample Location	Temperature	CVN, ft.lb
"Austempered"	From 1.5 in keel bar	+75 F	20-22-19
Normalized	From 1.5 in. keel bar	+75 F	34-33-32

Note: All tests in Tables 4-6 were performed as per ASTM A370.

It is seen that the tensile strength and the yield strength values are marginally better in the "austempered" bars than in the normalized test pieces. The BHN of the "austempered" test piece is significantly greater than explained that of the normalized test piece. However, the Charpy V-notch energy values are significantly *lower* in the "austempered" test piece than in the normalized test piece.

The customer's requirement for normalized (1650 F) and tempered (1250 F) castings made from ASTM A487 Gr. 4 at Quality Electric Steel are: Tensile Strength: 90,000 psi and Yield Strength: 60,000 psi. It is evident from Table 4 and Table 5 that these requirements are met both in the "austempered" and normalized (not tempered) test pieces. However, in a truly austempered steel casting, the yield strength is only about 10% lower than the tensile strength. The trend shown in the present "austempered" sample is thus more in line with a normalized sample than with a truly austempered sample. The tensile strength-to-yield strength ratios are similar at a given hardness in austempered and quenched-and-tempered samples. (A typical ratio achieved at Quality Electric Steel for ASTM A487 Gr.4 in the quenched-and tempered condition is 1.17). Thus it may be inferred that the "austempered" sample in the present work (with an average ratio of 1.62) had a microstructure more related to the normalized state (average ratio of 1.63) than the austempered or quenched-and-tempered states. In other words, instead of the bainitic structure found in austempered state or tempered martensitic structure found in the quenched-and-tempered state, the sample would in all likelihood have a predominance of pearlite. The microstructure shown in Fig. of the 'austempered' sample shows, not surprisingly, a predominance of pearlite.

An examination of the temperature-time curve (Fig. 3) indicates that the soaking condition for austenitizing was according to normal practice. However, when the casting was transferred to the fluidizing furnace, the surface temperature dropped continuously in the fluidized bed, even though the fluidized bed temperature was reasonably steady. This suggests that the cooling rate of the casting was too fast for any arrest at the bainitic transformation temperature. While the cooling rate was not fast enough for martensitic transformation, the continuous cooling of the casting in the fluidized bed, instead of having an arrest of its temperature at around the fluidized bed temperature resulted in the predominant formation of pearlite instead of bainite. In what follows, the likely reason for this undesirable result will be discussed.

In a fluidized bed, unlike in a salt bath, both conduction and convection play equally dominant roles in determining the heat exchange between the fluidized bed medium and the product being heat treated. If the heat exchange process is such that more heat flux is lost by the product than gained by it from the medium, the product would continuously cool, assuming that it was at a higher temperature than the fluidized bed at the time of immersion. This seems to have occurred in the present experiment. The obvious solution is to equalize the heat loss and heat gain. This, in principle, can be achieved in the present case by increasing the heat flux into the casting and reducing the heat loss from it. In the absence of sufficient data on the thermal characteristics of the systems used, it is not possible to make definite recommendations for remedy. However, it appears that the fluidizing agent velocity in the bed was too high in the present experiment, contributing to increased convective heat loss from the casting and restricting the time for conduction heat transfer to occur between the hot medium and the casting. Also the use of a medium with lower conductivity in the medium may have helped to decrease the heat loss from the casting.

On the positive side, however, was the observation that the casting "austempered" in the fluidized bed showed a much better surface quality than the air cooled casting, having minimal scale on the surface. Since both the castings were austenitized under similar conditions, it may therefore be inferred that the fluidized bed treatment results in better surface finish as a result of the mild "shot peening" action of the fluidized bed.

SUGGESTIONS FOR FUTURE WORK:

1. Develop a process model using the finite element method to study the temperature profiles in the fluidized bed as a function of the medium variables such as the type of medium, type and rate of flow of the fluidizing agent, pressure drop across and along the bed and furnace variables like power input, nozzle shape and size (membrane design) and others. Next it is necessary to model the heat exchange between the fluidized bed medium and the test casting. For this purpose, it is necessary to determine the heat transfer coefficient in the fluidized bed at the casting/medium interface as affected by the above variables. It would therefore be strongly advisable to seek supplementary funding to make the fluidized bed fabricated by Quality Electric Steel fully functional to facilitate the collection of data noted above.
2. Couple the model with the temperature-time-transformation (TTT) diagram for the steel under consideration and select a good combination of the variables for the austempering condition to be achieved, i.e., equilibrium of heat flow between the medium and the casting during austempering at a given temperature.
3. Perform experiments in the furnace and adjustments in the model interactively to get the desired results with actual castings subjected to austempering.

4. Once the prototype shows repeatable desired results, incorporate the conveyor system for continuous austempering.

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Fig. 1. Schematic Diagram of Fluidized Bed Furnace

Fig. 2. Cast Steel Keel Block for Austempering