Jet Impingement Furnace For The Solution Heat Treatment Of Aluminum Castings

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Abstract

Short cycle heat treatment of aluminum castings has been shown to be possible in laboratory environments. But the Industry awaits a production furnace that looks and operates like a conventional mass flow convection furnace, but has the heating rate, heating rate uniformity and temperature uniformity that makes short cycle solution heat treatment possible. Temperature uniformity in mass flow furnaces has been addressed. Development in fan design and implementation of Jet Impingement heat transfer has improved heating rate. But, uniformity of heating rate, which is essential to the Time-Temperature requirements of solution heat treatment, has not been fully solved. To that end, SECO/WARWICK Corporation embarked on a development program to solve the problem of Uniformity of Heating Rate in a Conventional Mass Flow – Jet Heating Furnace for the Solution Heat Treatment of Aluminum Castings, and was awarded a patent in February 2006 for the resulting design.

Introduction

Two characteristics of heat processing furnaces that are of great importance are heating rate and temperature uniformity and the furnace user and the furnace manufacturer strive to continuously improve these characteristics. The reasons are obvious. Improved heating rate reduces cycle time; improved temperature uniformity improves product quality and product yield rate. And currently, there is the desire to replace batch processes with in-line processes, if these two characteristics can be improved dramatically. This desire is also obvious. An in-line process would reduce product inventory and in many cases, the heating and handling of product fixtures or baskets. One such case would be short cycle solution heat treatment of aluminum castings. Short cycle heat treatment of aluminum castings has been shown to be possible in laboratory environments. But the industry awaits a production furnace that looks like and operates like a conventional mass flow convection furnace, but has the heating rate, heating rate uniformity and temperature uniformity that makes short cycle solution heat treatment possible. Temperature uniformity in mass flow furnaces has been addressed. Development in fan design and implementation of Jet Impingement heat transfer has improved heating rate. But, uniformity of heating rate, which is essential to the Time-Temperature requirements of solution heat treatment, has not been fully solved. To that end, SECO/WARWICK Corporation embarked on a development program to solve the problem of Uniformity of Heating Rate in a Conventional Mass Flow – Jet Heating Furnace for the Solution Heat Treatment of Aluminum Castings.

Conceptual Design

The conceptual design of this new Mass Flow – Jet Impingement Furnace is shown in Figure 1. Generically, it looks like a conventional up flow, convection type, roller hearth furnace. The recirculating fan is in the roof of the furnace, the air flow exits the fan and is turned downward, heat is introduced, the air flow is then turned upward through the rolls and then it is returned to the inlet of the fan. But, in this furnace design, what happens to the air between the fan outlet and the fan inlet is significantly different than what the air experiences in a conventional mass flow furnace.

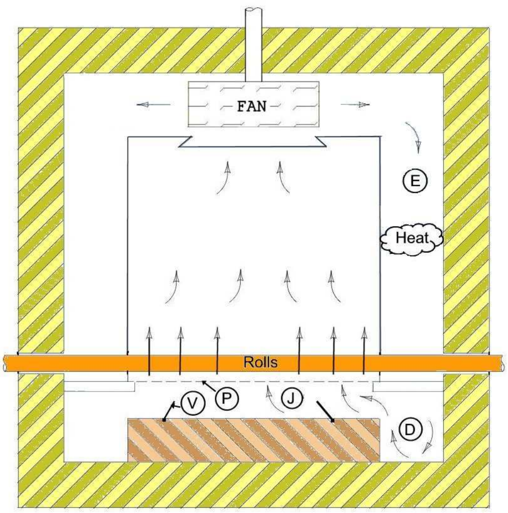

Fig. 1 Mass Flow – Jet Impingement Furnace

When the air exits the fan it enters the Expansion Chamber E, where in the absence of any turning vanes, the dynamic pressure of the air is immediately converted to static pressure when the air impinges upon the vertical wall of the chamber. Also, when the air strikes the vertical wall, there is equal probability that the air will be directed longitudinally (into and out of the paper) as well as downwardly. Thus, uniform distribution of the airflow is initiated. The air flow progresses downwardly and, again without any turning vanes, the air enters the Distribution Chamber where the longitudinal distribution of the air is completed before it enters the Jet Chamber J . The air then exits the Jet Chamber through a Jet Impingement Plate P that creates high velocity Jets for enhanced heat transfer to product that is placed on the furnace rolls.

The design of the Jet Chamber is the final critical design of this furnace concept. Without proper design, the airflow would not be uniform horizontally across the Jet Plate. Since there are practical restrictions on furnace dimensions, the volume of the Jet Chamber cannot be made large enough to create uniform static pressure below the Jet Plate in order to create uniform airflow through the Jet Plate. Unless the bottom of the Jet Chamber was contoured or a Distribution Vane V was placed in the Jet Chamber, there would always be more airflow at the center of the Jet Plate than at the edges of the Jet Plate because of the forward velocity of the air in the Jet Chamber. Contouring would be furnace specific and non-adjustable, so the vane approach was chosen.

Furnace Description

A photograph of the development furnace is shown in Figure 2. As discussed above, the hearth is a conventional roller with 12 – two (2) inch diameter 304 SS rolls on six (6) inch centers. The active hearth dimensions (jet area) are 4 Ft by 4 Ft. The furnace has a front and rear fiber lined door with the weight of the door providing an air seal to the furnace case. The door openings are 52 inches wide by 16 inches high. The thermal insulation is 8 inches thick and there is an inner liner of 304 SS. The rolls are driven with a variable speed drive and can be oscillated at variable time intervals. Air is re-circulated with two (2) forward-curved multi-blade fans (one on each side) connected in parallel to a variable speed drive. The fan speeds were matched through sheave selection. The total maximum airflow is in the range of 17,000 acfm. The furnace is electrically heated with a total power input of 25 KW. The temperature is controlled by two (2) proportional - SCR control loops (one for each side). Below the rear door is a temperature controlled re-circulating water quench tank. The furnace is manually loaded and unloaded from an auxiliary roll table. When quenching is required, the product is pushed out the rear door onto an inclined ramp and the product slides into the quench tank.

Fig. 2 Development Furnace

Air Flow Uniformity

Before the furnace was heated, the pressure at individual Jet Holes was measured in order to establish the uniformity of airflow over the entire area of the Jet Plate. The method of testing was to measure the total pressure at the center of a Jet Hole, using a probe as shown in Figure 3, with a four (4) inch long inclined manometer having a pressure of 0.02 inch w.c. as the smallest measurable increment. This arrangement, assuming the static pressure at the surface of the Jet Plate was uniform, would yield accuracy in the Jet Velocity of 0.5%. (Measured pressure was greater than 2-inch w.c.)

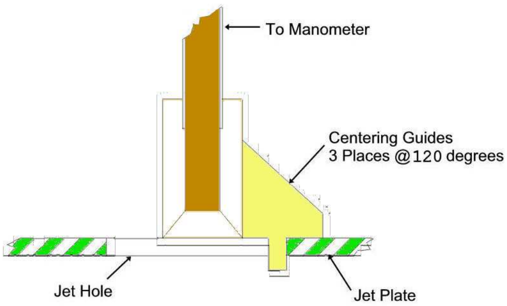

Fig. 3 Probe

As anticipated, the pressures in the longitudinal direction (front to back) were uniform. The absence of turning vanes and the two chambers, the Expansion and the Longitudinal Distribution Chambers, created this longitudinal uniformity. Also as anticipated, the pressures in the horizontal direction (sides to center) were not uniform with the pressure at the center being the highest due to the dynamic energy in the air as it entered the Jet Chamber.

Several geometries/interrupting vane configurations in the Jet Chamber were investigated until a suitable arrangement was found. It was found that simple front to back vanes, one on each side, yielded excellent uniformity. In this furnace, the vane position and angle were adjusted using the port below the Jet Plate, as shown in the photograph. In future furnaces, adjustment of the Horizontal airflow would be made at startup by external means.

Pressure measurements were systematically and randomly made across the entire Jet Plate. The results of this investigation showed uniformity in pressure between individual Jet Holes was +/- 4 % with a corresponding variation in velocity of +/- 2 %. The variation in pressure appeared to be random, that is, a systematic variation in either the horizontal or longitudinal direction was observed. At maximum airflow conditions, Pilot tube measurements showed the Jet Velocity was an average of 105 ft/sec. The air temperature for this detailed testing was in the 150 deg F range. Pressure measurements at higher air temperatures indicated that airflow uniformity improved as furnace temperature increased and the Jet Velocity increased to an average of 125 ft/sec.

Temperature Measurement and Data Acquisition System

When developing new equipment and the product uniformity requirements are +/- 5 deg F or less, accurate "real time" temperature monitoring of the product is essential. To that end, the trailing thermocouple method with a custom designed data acquisition system was used for temperature monitoring of the product. And, considerable care was given to the accuracy of the data acquisition system, to the thermocouple accuracy and the placement of the thermocouples in the product.

An Allen Bradley PLC with three (3) T/C input modules (Model No. 1746-INT4) were used to collect the data from twelve (12) Type K Thermocouples. The data was displayed real time on a computer screen and at a specified time interval (minimum of two (2) sec) the data was written to an Excel file utilizing InTouch®[1] and was recorded in a moving register on the computer screen. The previous twenty (20) data scans were displayed on the computer screen. With this program (1) the current temperature could be continuously monitored, (2) the temperature history could be monitored and (3) a permanent record of the data was written in an Excel file.

Through InTouch, each of the twelve (12) T/C inputs could be biased with respect to a reference temperature signal. This was done at a "reference temperature" of 1000 deg F to an accuracy of +/- 0.1 deg F. The amount of bias was less than 2 deg F. The accuracy of +/- 0.1 deg F was due to the temperature stability of the reference source and the input modules. (Each has internal ambient temperature compensation and the required bias could be the result of many factors)

The thermocouples were Type K fabricated from Omega "special limit of error" 24 gauge wire with 1300 deg F glass insulation. The thermocouple junction was "welded" with a propane – oxygen torch without the use of any intermediate material. The configuration of the junction and the placement of the junction in the product are shown in Figure 4.The T/Cs were terminated and connected to the data acquisition system using miniature T/C male/female connectors. The small 24gauge wire was used so that temperature response would be fast, that error due to heat conduction from the heated air to the T/C junction would be minimum and that a bundle of twelve (12) thermocouples would be small and convenient to manage as trailing thermocouples.

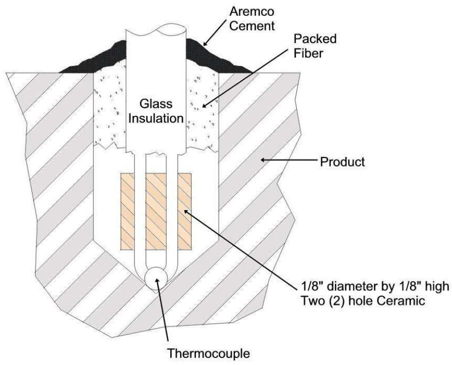

Fig. 4 Thermocouple Configuration

"Special limit of error" wire has a guaranteed absolute accuracy of 4 deg F at 1000 deg F. In practice, the wire is significantly more accurate than the guarantee. The spools of wire used in this development project had a deviation from standard of 0.0 and + 0.9 deg F at 800 deg F. Also, experience has shown that when purchasing thermocouples where beginning and end of the wire spool is certified, the uniformity is within +/- 0.25 deg F.

Thus, it is reasonable to neglect deviations between individual T/Cs when T/Cs for a given test were fabricated from the same continuous length of wire. As to the absolute accuracy of these fabricated thermocouples, this was established by comparing a fabricated T/C to a certified T/C closely coupled in an air stream at 1000 deg F. This comparison showed that the fabricated T/C measured + 0.4 to + 0.8 deg F higher than the

[1] *InTouch®, InControl® and Wonderware® are trademarks of Invensys plc, its subsidiaries and affiliates.*

certified T/C which agreed with Omega's specifications. Thus, any absolute or relative T/C error was neglected in reporting test results.

Product Temperature Uniformity

In many heat processing applications temperature uniformity of the product at end of cycle is sufficient criteria for producing an acceptable product. Examples of such processes would be reheating metal for rolling and forging and some applications of hardening steel. But there are many applications in heat processing where time at temperature is the criteria. Even though the product temperature may be uniform at end of cycle, the product may not be acceptable because different sections of the product will have had different time at temperature histories. Examples would be solution heat treating of aluminum alloy and carburizing steel.

Volume to area ratios of various product sections as well as load densities will effect time at temperature but a more significant variable would be non-uniformity in the heat transfer rate of various locations in the Heat Processing Equipment. If the heat transfer rate at different locations is not uniform, product temperature as a function of time will not be uniform, because product temperature is a function of the heat transfer rate times the difference in equipment temperature and product temperature. Thus, at end of cycle, all sections of the product will not have the same history and all sections may not have acceptable properties. In many cases, extending the cycle time can minimize these differences in properties, but this is not a desirable solution for obvious reasons. Also, too much time at temperature may yield undesirable properties.

Thus, the important characteristics of Heat Processing Equipment are temperature uniformity and heating rate uniformity, and not simply temperature uniformity. In all cases, uniformity of heat transfer rate will improve product quality and reduce cycle time.

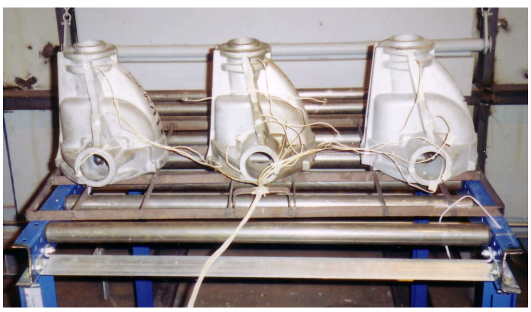

Fig. 5 Test load of Castings

In heat processing equipment, where convection heat transfer and process gas distribution contribute to product properties, the uniformity of airflow (process gas flow) is a dominant variable with respect to acceptable product properties. The Equipment design and the cold airflow testing as discussed above were the starting points of this development program but the success of the program could only be established through testing at temperature with usable production products. Figure 5 shows the product tested and the physical arrangement of the product.

Three differential aluminum castings were placed on a one-inch high open tray. They were spaced on 15 ½ in centers with the outside dimension of the three castings at 42 in. Each casting weighs 25 lbs with outside dimensions of 11 ½ in wide by 16 in deep by 12 ½ in high. The nominal hearth dimensions were 48 in by 48 in. Nine thermocouples, three on each casting, were placed as shown at a depth of one inch. (Before this test, a single casting was tested with six thermocouples and these three locations were identified as the last to heat positions.) The tray was pushed to the center of the hearth and oscillated front to back during the test a distance of 9 inches. (Rolls are 2 in diameter on 6 in centers.) The steady state target temperature was 1000 deg F. The test duration was 35 minutes.

The results of the test are shown graphically in Figures 6 and Figure 7. Figure 6 shows Temperature vs. Time for the complete test and Figure 7 shows Temperature vs. Time in an expanded scale beginning when all temperatures were above 995 deg F. Series 10 in the graphs is furnace control temperature that shows a decreasing thermal head as the castings reached target temperature.

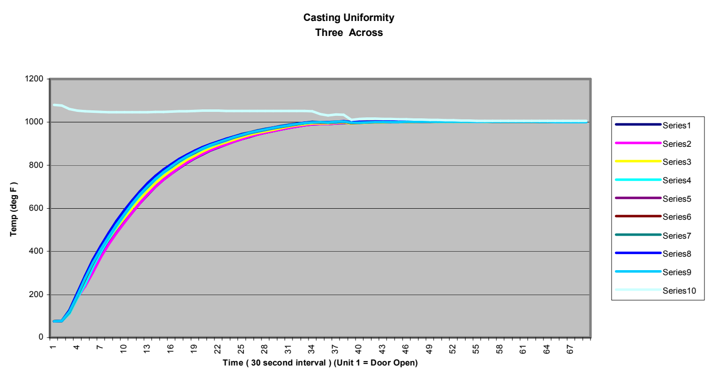

Fig. 6 Temperature vs. time for the complete test

The data shows that the temperatures at the top of the castings, being the greatest distance from the heat source (the jet plate), lagged slightly those at the bottom and midpoint of the castings until all temperatures were above 995 deg F. At this point in the cycle, all temperatures were within +/- 2½ deg F and none ever exceeded 1003 deg F. At steady state individual castings were within 1 deg F and side-to-side variation was within 2 deg F.

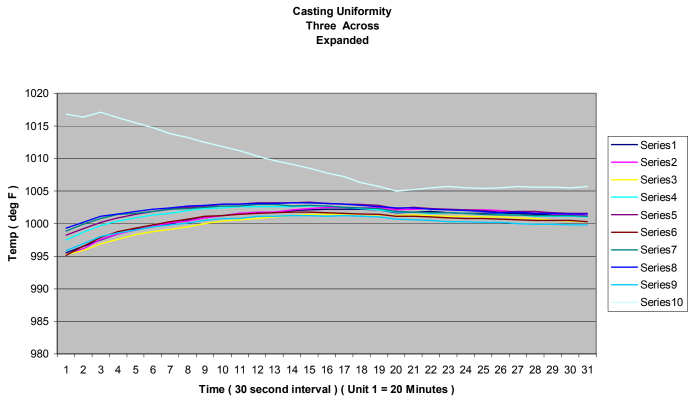

Fig. 7 Temperature vs. Time in an expanded scale beginning when all temperatures were above 995 deg. F

Heat Transfer Rate

The jet plate in this furnace design serves two purposes. It is a means to distribute the airflow uniformly over the entire hearth area and it produces high velocity air jets that create an enhanced heat transfer rate to the product (heat transfer coefficient). In order to compare the heat transfer coefficient of this jet-heating furnace to that of a conventional mass flow furnace, a series of heat transfer rate tests were conducted using aluminum plates. In mass flow systems, distance is not a variable with respect to the heat transfer coefficient but in jet systems the distance from the jet plate to the product (target distance) is a significant variable. Therefore, the heat transfer coefficient tests included target distance as a variable.

The method used to determine the heat transfer rate was to heat an Aluminum plate using a constant furnace temperature and to record the temperature of the plate as a function of time. Then, by determining the heat gained by the plate for a known time interval and equating this heat gained to the heat transferred by convection and radiation, a total heat transfer rate could be determined, i.e.,

$$(ht)(A)(To - Tp)(\Delta\theta) = (cp)(W)(\Delta T)$$

where W = weight of the plate

cp = specific heat of aluminum at average plate temperature Tp

ΔT = temperature gained by the plate in the time interval $\Delta\theta$

A = area of the plate exposed to the furnace temperature To

A = nominal plate area x view factor

ht = total heat transfer rate (total heat transfer coefficient)

Thermal insulation was placed on five (5) of the six (6) surfaces of the plate with only the bottom surface exposed to the impinging jets of air. In this manner the heat transfer area was well defined and all jets were perpendicular to the plate.

Figure 8 is a graph of Plate Temperature vs. Elapsed Time (heating curve) for a one (1) inch thick 6061 Aluminum plate at a distance of 4 ¼ inches from the jet plate. One third (1/3) of the plate area was blocked by the furnace rolls. The plate was in a frame and was oscillated on the furnace rolls so that the entire plate surface received direct impingement of the jets during a portion of the test. The temperature of the plate was measured at four (4) places, three (3) corners and the center of the plate. The thermocouples were at a depth of one half (½) inch. Air temperature was measured at two (2) places beside the plate. The seventh temperature shown on the graph is furnace control temperature. Temperature data were recorded at 30-second time intervals.

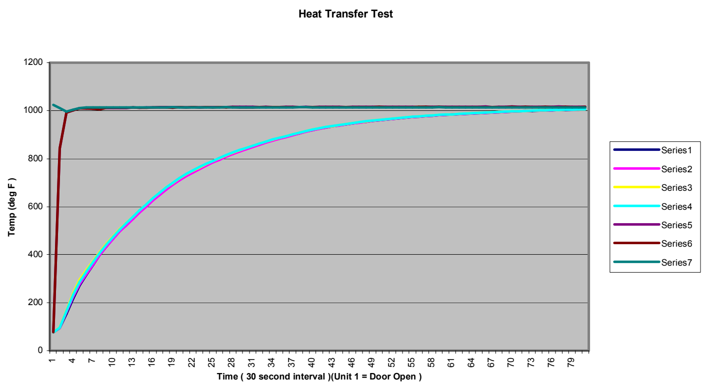

Fig. 8 Plate temperature vs. elapsed time (heating curve) for a one inch thick 6061 aluminum plate at a distance of 4-1/4 inches from the jet plate

The total heat transfer coefficient was calculated at five (5) temperatures of the heating curve at nominal temperatures of 400, 500, 600, 700 and 900 deg F using recorded adjacent data points at 30-second time intervals. It was assumed all heat was transferred through the bottom of the plate and the plate area view factor was 67 %. Tabulated values for the specific heat of

Aluminum were used. These calculations yielded a value of 39 +/- 4 Btu/Hr-SqFt-deg F for the total heat transfer coefficient. The radiation contribution to this value was estimated at 3 Btu/Hr-SqFt-deg F. Using this calculated value, the error resulting from the assumption that all heat entered the plate through the bottom surface was estimated to be a reduction of less that 2 Btu/Hr-SqFt-deg F. With these estimates of heat gained by radiation transfer and heat gained through the plate insulation, it should be safe to say that the convective heat transfer coefficient resulting from this evaluation would be in the range of 30 to 35 Btu/Hr-SqFt-deg F. Using the same procedure, the heat transfer coefficient was measured at target distances of 7 ½ and 14 ½ inches with values for the total heat transfer coefficient of 29 and 14 Btu/Hr-Sq Ft-deg F respectively compared to a value of 39 Btu/Hr-SqFt-deg F at a target distance of 4 1/4 inches. Mass flow furnaces, due to maximum fan capacity with respect to furnace size, typically have a value of 10 Btu/Hr-SqFt-deg F. Thus, this jet system yielded significant improvement in heat transfer rate.

Application to Short Cycle Solution Heat Treatment of Aluminum Castings

It has been known that in line - short cycle Solution Heat Treatment of Aluminum Castings rather than the current practice of batch heat treating would be possible, if a furnace were available that provided rapid heating to the castings, if the furnace produced temperature uniformity in the castings when solution temperature was reached and the furnace maintained a stable temperature during the solution treatment.

This development furnace exhibited these requirements, thus, short cycle - Solution Heat Treatment was investigated. The investigation was the individual Heat Treatment of a series of castings followed by identical metallurgical examination. The heating procedure for each casting was identical as was the quench and aging procedure. The hold time prior to quench was the only variable in this series of tests. This was varied from 0 to 180 minutes hold time.

The casting used for this investigation was the casting that was used for determining product temperature uniformity as discussed above. The casting material is modified 319 Alloy. The castings were obtained form our customer who is currently batch heat treating them in a SECO/WARWICK Furnace System so that reference metallurgical properties are documented for comparison to the results obtained from this investigations.

Three temperatures were monitored for the Solution Treatment of this series of tests, namely, furnace control, casting temperature and ambient temperature near the casting.

Figure 9 and shows these temperatures (typical) during the heat/hold portion of the heat treat cycle and Figure 10 shows the casting temperature and the ambient temperature (typical) during the quench cycle.

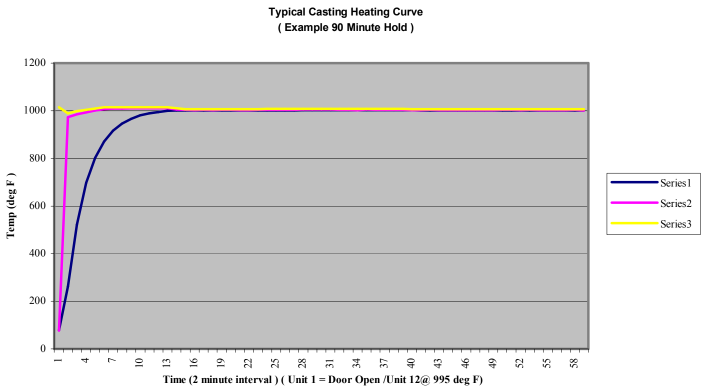

Fig. 9 Typical casting temperature and ambient temperature during the quench cycle

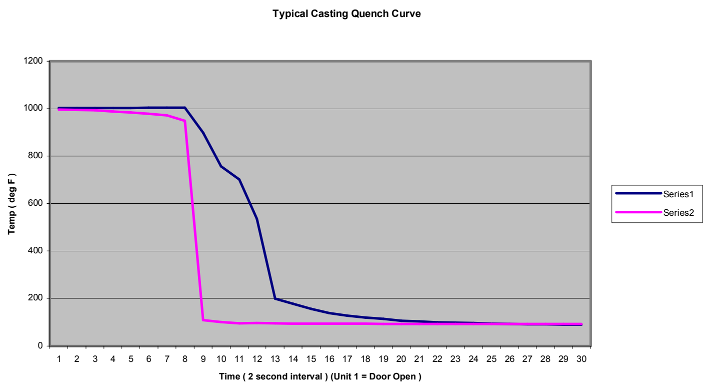

Fig. 10 Typical temperatures during the heat/hold portion of the heat treat cycle

The Solution Heat Treatment procedure was as follows:

1. Stabilize the furnace at 1015 deg F;
2. Open the front door of the furnace and start the data acquisition system;
3. Push tray and casting into furnace and immediately close door;
4. At 24 minutes lower furnace set point to 1007 deg F;
5. At 25 minutes start the hold time;
6. After hold time open rear door and immediately push into quench tank;
7. Remove casting from quench and begin the aging procedure.

Table I. Metallurgical Results for Production Castings

Hold Time	UTS	YS	Elongation
(Minutes)	(Mpa)	(Mpa)	(%)
Position A			
0	283.6	217.0	4.36
5	276.7	212.8	3.76
10	277.6	220.7	2.97
20	292.8	216.1	6.05
30	300.0	240.6	5.65
60	300.0	217.0	7.58
90	290.5	224.0	2.96
180	294.5	228.1	6.19
Position B			
0	283.4	206.9	5.90
5	291.6	219.1	5.71
10	271.3	199.8	3.40
20	277.0	206.5	4.22
30	292.9	215.2	7.60
60	300.3	227.6	7.23
90	304.7	230.4	8.56
180	297.1	226.5	9.99
Position E			
0	248.9	194.1	2.15
5	260.1	188.1	3.8
10	249.2	177.3	2.83
20	261.1	198.0	2.71
30	275.6	208.0	5.20
60	264.5	206.8	3.16
90	275.8	212.6	2.97
180	269.6	211.3	2.96
Position F			
0	248.7	177.6	2.44
5	249.5	195.6	2.24
10	249.9	185.1	2.37
20	246.6	191.4	2.07
30	259.4	199.8	3.31
60	273.1	209.5	4.26
90	272.4	218.0	2.97
180	268.1	199.5	4.56

Eight castings were Heat Treated and sent to our customer for metallurgical evaluation. The result of the metallurgical testing of these eight casting is shown in Table I. Normal properties for Ultimate Tensile Strength, Yield Strength & Elongation at positions A & B are 300, 230 & 9 and for positions E & F they are 270, 210 & 4.

Our customer commented that the properties at hold times of 30 minutes and greater are acceptable. For hold times less than 30 minutes - 85 to 90 % of the required strength was obtained with scatter in the required elongation of 60 to 80 %.

Summary

A New Mass Flow – Jet Impingement Furnace design has been developed and a production prototype has been built and tested. This furnace has shown an unsurpassed combination of mass flow uniformity, heat transfer rate, product temperature uniformity and product temperature stability during heat treatment than any known convective type furnace. Short Cycle Solution Heat Treatment of Modified Aluminum Castings has been investigated.

The uniformity of mass flow across the 48 inch square hearth is better than +/- 2%; a convective heat transfer coefficient of 35 Btu/Hr-Sq Ft- deg F has been measured; temperature uniformity at 1000 deg F of three 25 lb production castings spaced across the hearth was measured at 2 deg F with an individual uniformity of 1 deg F; product temperature stability during the solution heat treatment investigation was 1 deg F. The solution heat treatment cycle of production modified 319 Aluminum castings (heat to quench) was varied from 25 minutes to 205 minutes. Metallurgical evaluation showed that a 55 minute cycle for this particular casting was sufficient time to obtain acceptable properties with no improvement in properties as the cycle time was increased.

References

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R1, Original paper presented at the ASM 2005 Heat Treat EXPO, Pittsburgh, PA USA, www.asminternational.org