Development of a combined hot isostatic pressing and solution heat-treat process for the cost effective densification of critical aluminum castings

By:

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Abstract

To minimize the production cost and time of the heat treatment of critical application aluminum castings within the automotive industry a combined hot isostatic pressing (HIP)/solution heat treat process is desired. A successfully combined process would produce parts of equal quality to those produced by the individual processes of HIP and subsequent heat treatment with increased efficiency in time and energy. In this study, an experimental combined process was designed and implemented in a production facility. Industrially produced aluminum castings were subjected to the combined process and results were quantified via tensile and fatigue testing and microscopic examination. Comparisons in fatigue and tensile strength were made to traditionally HIPed and heat treated samples, as well as un-HIPed samples in the T6 condition. Results show that castings produced with the combined process show fatigue properties that are equal in magnitude to castings produced with the independent HIP and heat treatment processes. Furthermore, an order of magnitude improvement in the fatigue life in those castings that were produced with the combined process exists compared to the castings that were only heat treated.

This study shows no difference in the tensile properties that result from any of the processing routes compared. Also, microstructural comparison of the castings processed show no difference between the process routes other than porosity, which is only evident in the un-HIPed samples. Dendrite cell size and dendritic structure of the samples that were solutionized for the same time is identical.

Theoretical examination of the combined process was also completed to quantify the energy consumption of the combined process compared to the independent processes.

Thermodynamic calculations revealed that the energy consumed by the combined process for a typically loaded HIP vessel is fifty percent less than the energy required to process the same quantity of castings with the two individual processes. However, it was determined that a critical ratio of the volume occupied in the HIP vessel by castings to the total HIP vessel volume exists that ultimately determines the efficiency of the combined process. This critical ratio was calculated to be approximately fifteen percent. If the volume ratio is less than fifteen percent then the combined process is less energy efficient then conventional processing. These thermodynamic calculations were experimentally verified with power consumption process data in a production facility.

In addition, the time required for the combined process of HIP and solution heat treatment was calculated as thirty-percent less than the conventional two-step process. This calculation was verified via the comparison of data compiled from the experimental combined process.

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1. Introduction

The use of A356 (7%Si, 0.4%Mg) aluminum castings in the automotive industry is increasing due to the high shape complexity and the good strength-to-weight ratios that can be obtained with these parts. However, these parts in the as-cast condition are restricted in the applications in which they can be employed due to poor mechanical properties. These poor mechanical properties stem from two fundamental issues of the alloy in the as-cast condition.

The first issue with these castings is caused by inhomogeneity in the casting alloy during solidification. This non-uniformity is caused by inconsistent cooling within the mold and leads to an uneven dispersion of coarsely formed precipitates in the alloy matrix. This in turn leads to poor tensile properties in the as-cast condition.

The second issue inherent in as-cast microstructure is porosity. This porosity is classified as two distinct varieties, shrinkage porosity and gas porosity. Shrinkage porosity is caused by the volume of the liquid metal being greater than the volume of the solid metal. Gas porosity is caused by the high solubility of hydrogen in the liquid aluminum melt and the tendency for the hydrogen to come out of solution as temperature is reduced. Porosity is detrimental to the ductility, fracture toughness and fatigue behavior of the casting. Fortunately, for the casting industry, the issues inherent in the as-cast condition can be alleviated with post casting processing. Solution heat treating followed by aging is employed to refine the microstructure of the alloy and improve mechanical and physical properties. A densification process can eliminate the porosity in the casting.

Heat treatment for cast aluminum alloys starts with a thermal process to solutionize the alloy matrix, known as solution heat treatment, or solutionizing. Solution heat treatment uses an elevated temperature heat treatment to dissolve the second phase precipitates, change the morphology of the eutectic silicon phase and make the primary phase a homogeneous solid solution. In the case of A356, the precipitates are Mg_2Si. In order to prevent the Mg_2Si particulates from again precipitating out of solution, a rapid quench is employed. Quenching the castings also insures that the homogenization that results from the solutionizing step is maintained. To attain maximum strength in the casting a precipitation-hardening or aging heat treatment is employed. Artificial aging takes place at slightly elevated temperatures, 165°C, while natural aging occurs at room temperature. The homogenization attained in the previous steps insures a uniform dispersion of the particulates grown in the aging step. Artificial aging to reach maximum strength deems the temper of the casting as T6, where natural aging gives the casting the temper designation T4.

Hot isostatic pressing, or HIP, is typically performed before heat treatment and is a means of eliminating the porosity in castings. HIP surrounds the casting with a pressurized gas, which applies a hydrostatic force to the surface of the casting while at elevated temperature to facilitate material flow. The dominant densification mechanism in the casting during the initial stages of the HIP process is plastic flow. As castings spend additional time at maximum temperature and pressure the dominant densification mechanisms change, first to power-law creep, then to diffusional creep mechanisms (Nabarro-Herring, and Coble creep). The overall effect is the "welding" of isolated porosity within the casting [Atkinson].

Due to the time intensive nature of the HIP process, several variants of the original process have been developed to maximize the returns of the HIP process while minimizing process time and cost for the production of critical aluminum castings. Liquid hot isostatic pressing (LHIP) uses a heated incompressible liquid as the pressurizing media [Chandley]. The guiding principle behind this manufacturing process states that the majority of the time spent in the traditional gas HIP process is spent pressurizing and depressurizing the compressible gas media. In the LHIP process, the castings are immersed in the liquid salt bath and the entire salt bath container is pressurized via a hydraulic ram very quickly. By this method, maximum pressure can be reached in seconds rather then the several hours required in the HIP process. Furthermore, this process could be integrated into a continuous casting process [Chandley]. However, time spent at peak pressure for an A356 casting in the LHIP process is only about thirty seconds [Romano et al.], which does not allow any of the previously mentioned time-dependant creep mechanisms to occur.

Bodycote PLC has taken another approach to reducing the cost of the HIP process for aluminum castings. The Densal® process is a proprietary HIP process that has tailored the HIP process specifications and hardware specifically for aluminum castings. Time spent at temperature and pressure allows diffusional creep mechanisms to take place. It has been estimated that the Densal® process reduces the cost of HIP for aluminum castings by as much as seventy percent [Mashl et al.]. However, further gains in Densal® process economy may be possible. Due to the similarity of the process temperatures of solution heat treatment and the Densal® process, integrating these two processes could yield even further reduction in the cost of HIP and heat treatment for aluminum castings.

The purpose of this thesis is to develop and evaluate the feasibility of this combined Densal® + solutionizing process. The bulk of the work completed is included here as two papers to be submitted for publication. Each paper is a stand-alone work with separate abstract, introduction, procedure, results and discussion, conclusion and reference sections. The first paper included as Chapter 2 presents the experimental results of the process combination of Densal® and solution heat treatment on several Al-Si-Mg commercial castings. The second paper, Chapter 3, presents the results of the theoretical energy calculations of the combined process versus the individual processes of Densal® followed by subsequent heat treatment.

The development of a cost-effective means of producing critical application aluminum castings through simultaneous Densal® and solution heat treatment.

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Abstract

To minimize the production cost and time of the heat treatment of critical application aluminum castings within the automotive industry a combined hot isostatic pressing (HIP)/solution heat treat process is desired. A successfully combined process would produce parts of equal quality to those produced by the individual processes of HIP and subsequent heat treatment with increased efficiency in time and energy. In this study, an experimental combined process was designed and implemented in a production facility. Industrially produced aluminum castings were subjected to the combined process and results were quantified via tensile and fatigue testing and microscopic examination. Comparisons in fatigue and tensile strength were made to traditionally HIPed and heat treated samples, as well as un-HIPed samples in the T6 condition. Results show that castings produced with the combined process show fatigue properties that are equal in magnitude to castings produced with the independent HIP and heat treatment processes. Furthermore, an order of magnitude improvement in the fatigue life in those castings that were produced with the combined process exists compared to the castings that were only heat treated.

This study shows no difference in the tensile properties that result from any of the processing routes compared. Also, microstructural comparison of the castings processed show no difference between the process routes other than porosity, which is only evident in the un-HIPed samples. Dendrite cell size and dendritic structure of the samples that were solutionized for the same time is identical.

The experimental combined process also showed significant time savings within the scope of this production experiment.

1. **Introduction**

Aluminum casting represents an inexpensive method of producing parts with high shape complexity, excellent strength-to-weight ratios, and good corrosion resistance. For these reasons the use of aluminum castings in the automotive industry is on the rise. However, most aluminum alloys in the as-cast condition do not display the mechanical properties necessary for many applications, and therefore require subsequent heat treatment to optimize the microstructure of the alloy [1]. Furthermore, with the increased use of aluminum castings in cyclically stressed applications such as automotive suspension systems, maximizing the fatigue life of the heat-treated components becomes increasingly important. Densification, or the elimination of porosity inherent in the castings, is paramount in the production of fatigue-resistant parts, as pores are most often the fatigue-limiting characteristic in the casting. [2-6]. To date, microstructural refinement though heat treatment and fatigue-performance optimization through densification are completed as two independent processes.

In the case of most Al-Si alloys, the heat treatment manifests itself as an often lengthy solutionizing step, followed immediately by a rapid quench and a subsequent controlled age [1,7]. According to ASM International, heat treatment can take upward of eighteen hours to achieve a T6 condition for most Al-Si alloys [1]. Novel techniques of eutectic silicon modification do significantly reduce the solution heat treatment time, but densification steps are still required to improve the fatigue performance of the casting [9]. To this end, hot isostatic pressing (HIP) performed ***before*** the heat treatment process has proven to be an effective means of increasing the fatigue life of critical application parts by eliminating the shrinkage and gas porosities inherent in the casting. HIPed parts can see as much as an order of magnitude increase in fatigue life when compared to identical un-HIPed samples [2-6]. The HIP process surrounds the castings with a pressurized gas that imparts a hydrostatic stress on the component [10,11]. This compressive stress, in tandem with elevated temperature, shrinks and heals potential stress-intensifying pores. Initial densification occurs within the casting through time independent plastic flow. Then, under the conditions of time at elevated temperature *and* pressure, complete densification occurs via diffusional creep mechanisms [10,11]. The micrographs included below show the effects of HIP densification. The pores, marked with arrows, in the un-HIPed samples (Figure 1) are eliminated in the HIPed sample (Figure 2).

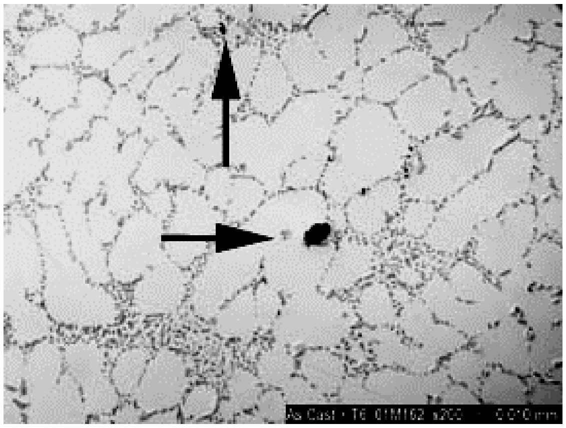


Figure 1 – Cast Al-Si-Mg alloy in T6 condition; arrows show porosity

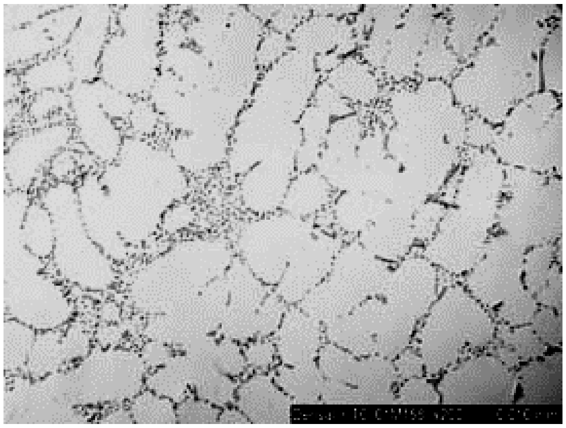


Figure 2 – Cast Al-Si-Mg alloy in HIPed T6 condition; no evidence of porosity

Currently, HIP is an independent process that increases the manufacturing cost of castings. In order to minimize this cost for aluminum castings, Bodycote PLC has developed a proprietary process known as Densal®. Densal®optimizes the HIP process and hardware specifically for aluminum castings and represents an advancement in the cost reduction of this process [6]. One of the most cost-effective current process for the production of critical application castings is the Densal® process followed by T6 heat treatment [6], yet it remains that while Densal® is a value-added process, costs in both time and energy are incurred from its use.

Due to the similarity of the peak temperature in both the HIP cycle and the solutionizing soak portion of the heat treat cycle, further integration of the two processes could save significant time and energy. There are difficulties inherent in this proposed combination. First, rapid quenching from the HIP vessel is currently not feasible due to the high pressure inherent in the HIP process. Secondly, even with eutectic-modification of alloys, the time at dwell temperature in the HIP vessel is usually not long enough for complete solutionizing.

The goal of this study is to investigate the feasibility of a combined commercial Densal®/solution heat treat process. This will be accomplished by designing and implementing an experimental combined process. Next, the effects of the combined process on the microstructure and tensile and fatigue properties of industrial castings will be investigated.

2. Experimental Procedure

A manufacturing procedure has been developed to test the feasibility of a combined HIP/solution heat treatment. The process modifies current HIP hardware to allow full solution heat treatment in the HIP vessel as well as the ability to quench from the solutionizing temperature. The thermal profile that a casting is subjected to during the combined process will be identical to that seen by a casting undergoing the independent solution heat treatment. Specifically, the temperature of the castings will be raised to the solution temperature, maintained for a certain dwell time, and then rapidly dropped via a traditional water quench. Going on concurrently to the solutionizing however will be the densification process. At the same time as the temperature of the casting is raised, the pressure of the gaseous media surrounding the casting will also rise to a prescribed value. This pressure will be only be maintained for the length of the standard Densal® dwell time and not for the entire solutionizing time. Pressure will be reduced while solution temperature is maintained and the remainder of the solutionizing time will be fulfilled.

One of the major questions that needed to be addressed to determine the feasibility of this combined process was whether the HIP furnace used had the sufficient power to overcome the adiabatic cooling that occurs in the vessel when the pressurized is vented. This issue becomes increasingly important when the heat transfer between the castings and the pressurized gas is considered. The operating pressure in the HIP vessel insures that this rate of heat transfer between the pressurized gas and the castings is on the order of ~100 W/m^2 K [12]. However, if the furnace can maintain the casting at the solutionizing temperature, $T_{solution}$, while the pressure within the vessel is reduced, then the vessel can be opened with the castings remaining at $T_{solution}$. This would then allow the castings to either be transferred to a soak furnace to continue the solution heat treatment or in special cases, water quenched. For simplicity, in this experiment the HIP vessel is used as a solutionizing soak furnace after the pressure is vented for the remainder of the solutionizing dwell. While this method would not be employed in an industrial practice, it does mimic the thermal profile that the castings would see in a production process. This process theory is further described in Figure 3, which graphically compares the thermal profile of the combined process to that of the typical Densal® cycle followed by subsequent T6 treatment.

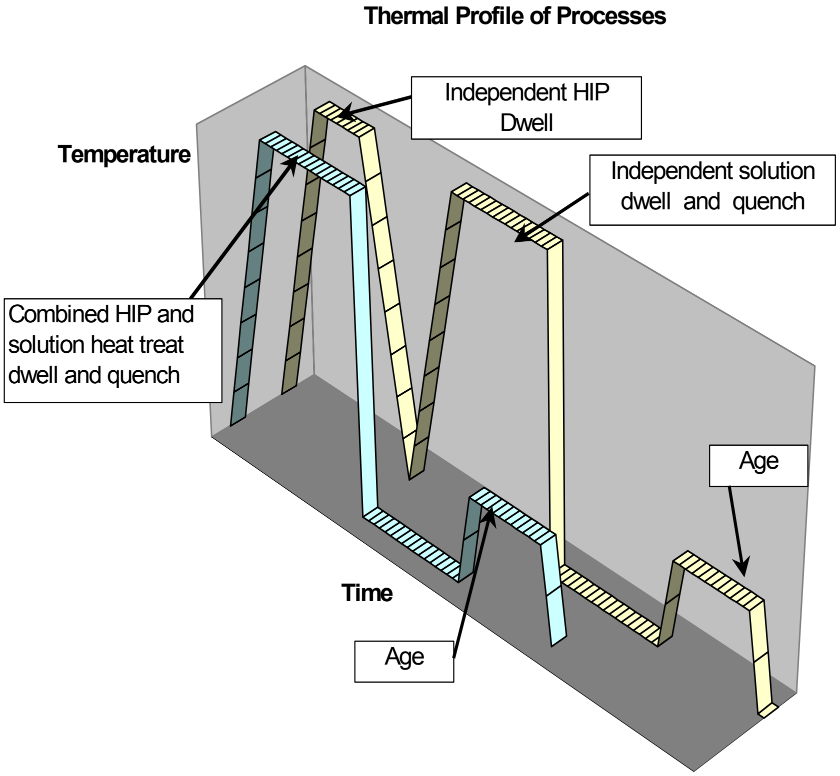


Figure 3 – Thermal profile of combined HIP/solution heat treat process (foreground) versus Densal® + T6 process (background). If the area under each graph (representing the energy used by each process) is compared, quite a large difference is noted.

The area beneath each process thermal profile represents a quantitative measure of the energy consumed during each of the processes. The graph shows that the energy consumed in the combined cycle may be significantly lower than that of traditional processing. Figure 3 also shows the predicted time savings that can be achieved by using the combined process. Again, the capability for this process to work in practice depends on the HIP furnace's ability to maintain $T_{solution}$ within the casting during depressurization. In order to determine the feasibility of the combined process, the following experiment was designed and conducted.

2.1. Testing Process Combination Feasibility

2.1.1. Materials and Processing

A casting with a high surface area-to-volume ratio was used to represent a "worst case scenario" of retaining heat during depressurization. The casting that was used for this experiment was a commercially produced Al-Si-Mg automotive ABS master cylinder housing. The casting is a relatively complex permanent mold part. Each casting is approximately 1kg in mass and 150mm by 150mm by 30mm in dimensions. Alloy composition of the castings, determined through Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), is included as Table I below.

Table I - Chemical composition of Al-Si-Mg ABS master cylinder housing casting determined via ICP-AES. Values are the averages of five readings performed on two different castings (ten total readings). The standard deviations for the calculations are included to show statistical variance in data.

	Si	*Mg*	*Fe*	*Ti*	*Sr*	*Cu, Mn, Ni, Zn*
Average Weight %	6.77	0.88	0.14	0.099	0.009	<0.035
Standard Deviation	0.118	0.022	<0.005	<0.003	0.000	<0.005

To show the relative complexity of the casting used, a sectioned view is included as Figure 4 below. Two thermocouples were used to record the thermal profile of the casting in the initial experiments and their location in the part is shown in Figure 4. The location of one thermocouple (TC) is marked in the three views with an "+". This TC measured the center temperature of the casting. The second TC, which is marked with an "o" in the figure, records the "skin" temperature of the casting.

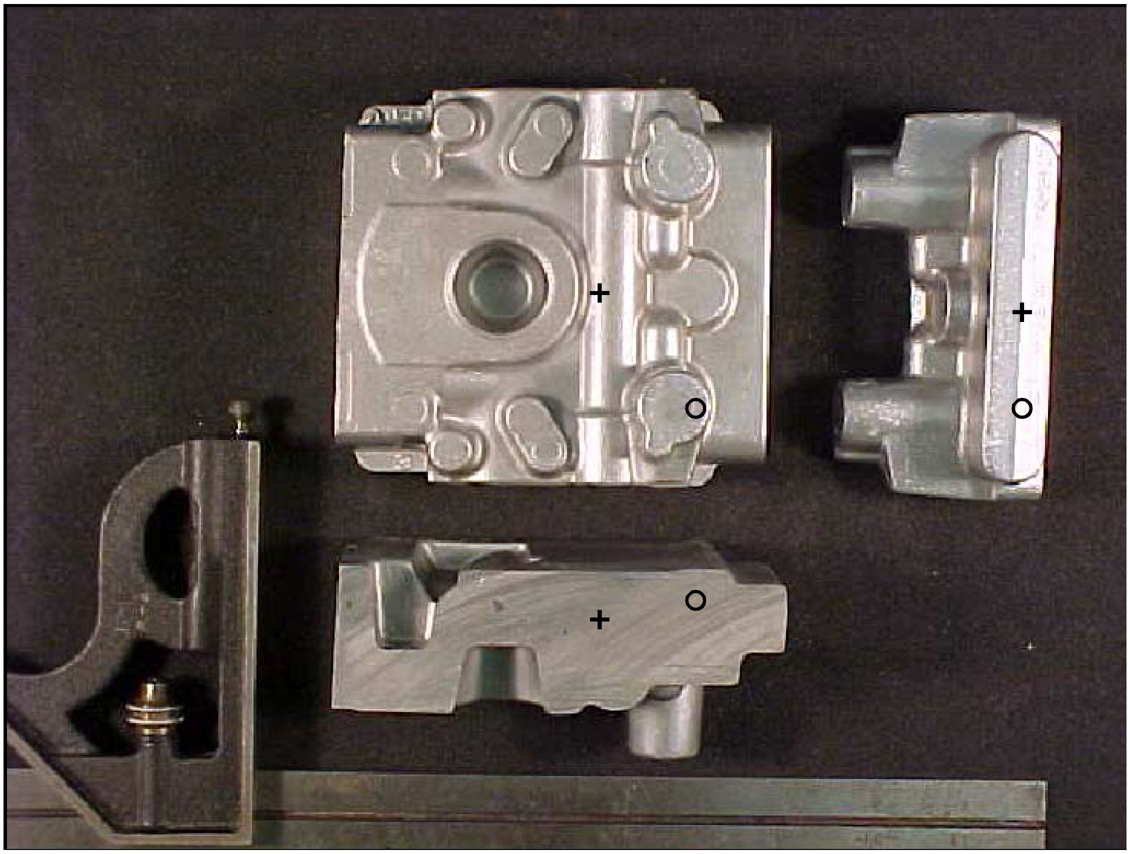


Figure 4 – Sectioned ABS master cylinder housing used in initial experiments. Location of two thermocouples marked in all views with + and o. (12-inch rule included to show scale)

The HIP vessel used was an ABB model at Bodycote IMT, Inc., in Princeton, KY. The working height and diameter of the HIP vessel are respectively 305mm and 205mm. Nitrogen gas was used as the HIP media. Time, temperature and pressure of the run followed the Densal® proprietary specifications. Normal processing dictates that at the end of the dwell portion of the Densal® cycle furnace power is shut off and gas pressure is vented. For this study, various vent times were experimented with to determine the maximum gas flow rate that could be achieved while maintaining the casting skin temperature at $T_{solution}$.

2.2. Mechanical Property Evaluation

2.2.1. Materials and Processing

To determine the effect of the combined HIP/solution heat treat process on the mechanical properties of selected industrial castings the following experimental matrix (shown as Table II) was developed.

Table II – Experimental matrix of post-casting processes specific to A356 aluminum parts

Process Designation	**Process Description**	**HIP CONDITIONS**					**HEAT TREATMENT**	
		$Temp_{MAX}$ (°C)	Time @ $Temp_{MAX}$ (minutes)	$Pressure_{MAX}$	Time @ P_{MAX}	Quench from HIP (yes/no)	Subsequent T6 Solution/ Quench	T6 Age (yes/no)
AC	As-Cast/T6	-	-	-	-	-	Yes	Yes
D	Densal/T6	Densal	Densal	Densal	Densal	No	Yes	Yes
4 HQ	Combined HIP/Solution HT and age	540	240	Densal	Densal	Yes	No	Yes
10 HQ	Combined HIP/Solution HT and age	540	600	Densal	Densal	Yes	No	Yes

This matrix was employed in all experimental runs that tested the processes of the combined HIP/solutionizing heat treatment route in order to make direct comparison of results possible. The as-cast sample is included in the process matrix as a baseline.

Densal® followed by conventional T6 heat treatment represents an existing commercial practice for the production of critical application parts. Two different combined process cycles were included in the matrix. The combined processes comply with current industrial practices of solution heat treatment. The process labeled 4HQ represents a relatively aggressive approach to solutionizing, as the total time at $T_{solution}$ is four hours. This dwell time is typical for solutionizing of eutectic modified alloys. 10HQ keeps the casting at $T_{solution}$ for ten hours, which is defined by ASM as the normal time for A356 sand-cast parts [1].

The T6 heat treatment of the un-HIPed and the Densal®-ed samples, as well as the aging of the samples subjected to the combined process were carried out to the following standards, shown as Table III.

Table III ASM specifications for sand-cast A356 T6 heat treatment [1]

	Time (Hours)	*Temperature (℃)*
Solution Heat Treatment	8-12	540
Water Quench	-	-
Age	3-5	155

2.2.2. Industrial Casting Tested

2.2.2.1. Commercially Produced ABS Master Cylinder Housing

The first run of processing was completed on the same ABS master cylinder housing as the *Process Combination Feasibility* testing described above. The experimental HIP unit described above was also used to process the HIPed samples. Each HIP run contained six castings to be used for mechanical testing and one casting instrumented as a control piece. The castings were arranged in such a manner to ensure quick unload and quench. The maximum measured delay from solutionizing temperature to quench was <45 seconds. The quench tanks were two twenty-liter cans with non-agitated water at room temperature (~25°C). To guarantee proper cooling only three castings were quenched in each can. Each processing category contained six castings, and each casting yielded two testing bars.

2.2.2.2. Experimental Coupon Wedge Castings

In order to have more control of the effects of microstructural constituents, these experimental castings were produced with standard industrial practices. These castings are approximately 127mm x 127mm x 25mm coupons and are made of strontium modified A356. Figure 5 shows the shape and relative size of the experimental coupon wedge castings.

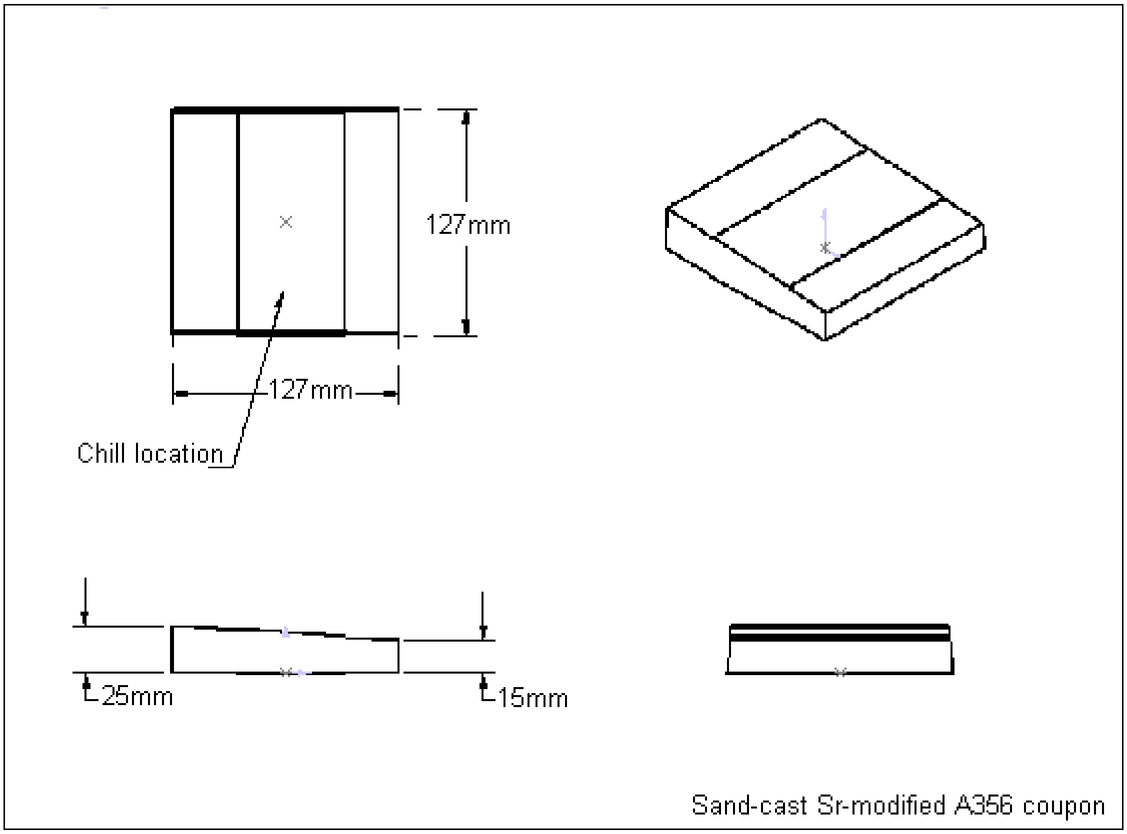


Figure 5 – Size and geometry of sand-cast Sr-modified A356 experimental coupons. Each casting yielded five tensile/fatigue samples.

The base alloy for the castings was a typical A356 (7%Si, 0.3% Mg, 0.08%Fe and balance Al), which was melted in an electric resistance-melting furnace. The alloy was then grain refined by adding a titanium-boron master alloy (10%Ti-1%B). The hydrogen levels within the melt were controlled via a rotary gas lance expelling argon into the melt. To prevent the dissolution of the Sr-modifier, the argon lance was removed before the modifier was added. The melt temperature was increased to 740°C for the mold filling step, and the melt was ladled into the molds after the dross was removed from the surface of the melt. The molds were two-part sand molds with two cast iron chills running perpendicular to the feed direction of the casting. The exact alloy composition for these castings was determined via ICP-AES and is included below as Table IV.

Table IV – Chemical composition of experimental coupon wedge castings determined via ICP-AES. Values are the averages of five readings. The standard deviations for the calculations are included to show statistical variance in data.

	Si	*Mg*	*Fe*	*Ti*	*Sr*	*Cu, Mn, Ni, Zn*
Average Weight %	7.08	0.37	0.06	0.158	0.012	<0.005
Standard Deviation	0.042	0.009	<0.005	<0.003	0.000	0.000

The same HIP unit described previously was used for both the combined processes (*4HQ* and *10HQ*) and the Densal® processed (*D*) samples. Nitrogen was again the pressurizing media. The quench protocol and facilities for the combined process samples were identical to that described in pervious sections. The time that it took for the castings to go from $T_{solution}$ in the HIP vessel to the water quench was again within the allowed quench delay of the material to insure supersaturation of Mg_2Si constituents. Process categories *D* and *AC* each contained two test coupons, while *4HQ* and *10HQ* contained three coupons total. Each coupon yielded five test bars.

2.2.2.3. Commercially Produced Steering Knuckle

The subjects of this round of processing and testing were sand cast, Sr-modified A356 steering knuckles castings shown in Figure 6.

Figure 6 – Commercially produced sand-cast Sr-modified A356 steering knuckles shown next to a penny to indicate scale. This casting represents the third industrial casting used to test the effects of the combined Densal®/solution heat treatment process.

Due to the size of these components processing was completed in a larger HIP vessel. The vessel used is at Bodycote IMT, Inc., in Princeton, KY. It has the working dimensions of 380mm diameter by 1194mm height. The vessel was modified to allow for rapid quenching from $T_{solution}$. Due to the increase in vessel size, ten castings were processed at the same time. To handle the increased quenching demand, two 200-liter water drums were used to quench the castings. The water was again at room temperature. The processing matrix for this experimental run was modified as the heat treatment for these parts dictated a 9-hour solutionizing dwell time rather than 10 hours. The 4-hour dwell process was still done to test the aggressive solutionizing approach. The castings subjected to Densal® followed by subsequent T6 treatment, as well as the castings that were not HIPed, were processed before the start of this experiment with normal commercial methods.

2.2.3. Mechanical Property Evaluation

2.2.3.1. Mechanical Testing

All samples groups that were destructively tested were subjected to tensile testing then high-cycle fatigue tests. Mechanical samples were fabricated in accordance to ASTM standards E9 for tensile bars and E466 for fatigue samples. All fatigue tests were of the axial variety and were performed at room temperature. Fatigue test specifications were determined from analysis of tensile results and each test's specifications are given in the *Results* section of this paper.

2.2.3.2. Material Characterization

Fractography to determine crack initiation sites was carried out on a JOEL 5900 scanning electron microscope (SEM). Backscatter Electron Imagery (BEI) was used in conjunction with Energy Dispersion Spectroscopy (EDS) in the form of a Phoenix EDAX system to identify oxides on the fracture surface. The microfractographic examination was done without knowledge of the samples' processing category to insure an unbiased evaluation.

3. Discussion and Results

3.1. Process Combination Feasibility

Figure 7 is included to show the results of the feasibility study. The graph shows the approximate pressure and temperature versus time. Units of pressure, temperature, power and time are omitted to preserve proprietary values. It is important to note that the temperature never leaves the approximate solutionizing range for the alloy being treated, either during the vent portion of the process, or during the subsequent solutionizing dwell portion of the process.

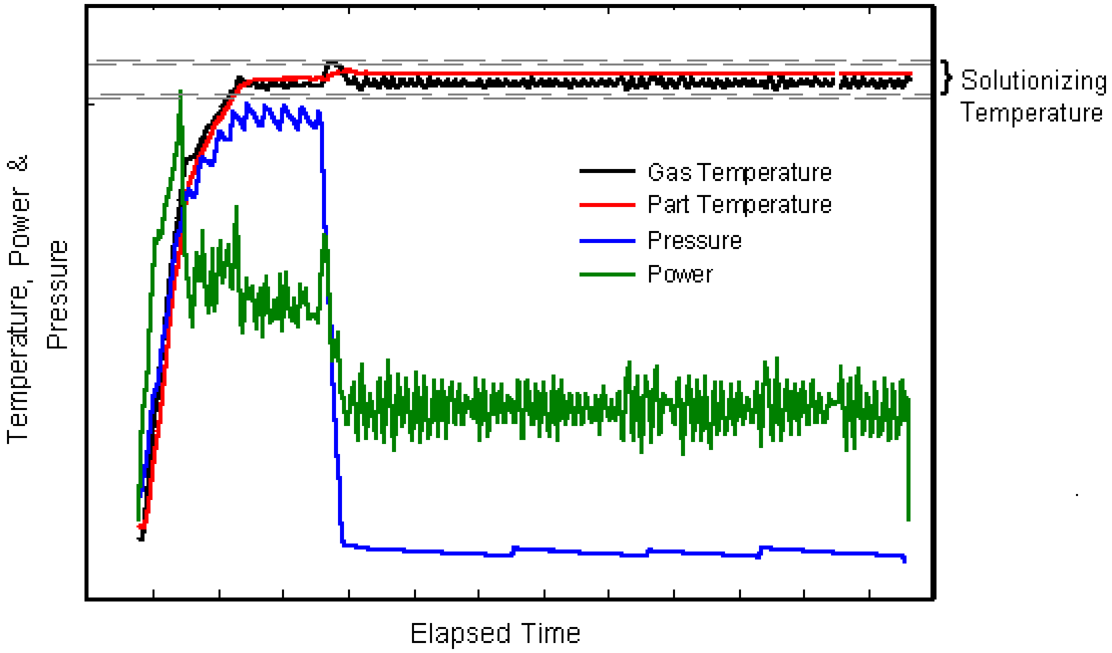


Figure 7 – Thermal profile of castings as pressure is vented during process feasibility study. Approximate gas temperature, and furnace power profiles are also included.

3.2. *Mechanical Property Evaluation*

3.2.1. Commercially Produced ABS Master Cylinder Housing

3.2.1.1. Microstructure

A microstructural comparison of castings in the as cast plus T6 condition as well as castings subjected to the Densal® plus T6 treatment are shown as Figures 1 and 2 earlier in this paper. The micrographs show that Densal® eliminates porosity in castings. Figure

8 shows the microstructure of a casting subjected to the combined process (4HQ). As is expected the micrograph shows no evidence of porosity in the sample and furthermore shows no difference between the dendritic structures of the castings subjected to the combined process or the independent processes.

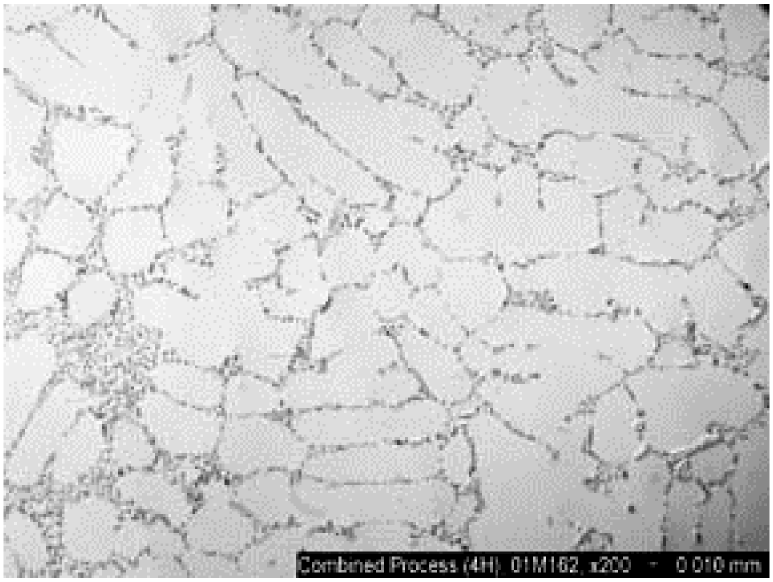


Figure 8 – Microstructure of casting subjected to the combined 4HQ process. The micrograph shows no difference in the microstructure of a casting subjected to a combined process compared to microstructures in Figure 1 and Figure 2. As expected no porosity is visible in the microstructure.

3.2.1.2. Tensile Results

Include below, as Table V are the measured tensile properties of the ABS master cylinder housing. Also included in Table V are calculated property mean values for each process group. Individual samples are labeled with a process group identification and tensile bar number. For example, 10HQ1, belongs to process group 10HQ, i.e. samples that are subjected to the combined process with a total dwell at $T_{solution}$ of 10 hours followed by a quench, the ‘1’ marks this samples as the first tensile bar of the group.

Table V – Tensile results of ABS master cylinder housing casting, reported with average values where applicable

Sample Designation	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Percent Elongation	Area Reduction Percent
AC1	291.6	321.3	0.7	2.0
AC2	293.7	329.6	0.7	2.2
Average	*292.7*	*325.4*	*0.7*	*2.1*
D1*	272.3	315.1	0.7	2.0
Average	*272.3*	*315.1*	*0.7*	*2.0*
4HQ1	299.2	335.1	0.7	3.2
4HQ2	308.2	338.5	0.7	1.0
Average	*303.7*	*336.8*	*0.7*	*2.1*
10HQ1	304.1	339.2	0.7	1.1
10HQ2	306.1	342.0	0.7	2.9
Average	*305.1*	*340.6*	*0.7*	*2.0*

** Only one sample is reported in Densal® (D) condition, as there was an error in testing.*

Tensile results of these castings show no significant difference in strength or ductility between any of the processes tested. This contradicts previously published works [2,4-6] that shows an increase in ductility when comparing HIPed and heat treated samples to non-HIPed and heat treated samples. The reason for this deviation from the ordinary in terms of ductility after Densal® can most likely be explained by oxide inclusions which happen to be present in the Densal® processed castings and not in the others.

3.2.1.3. Fatigue Results

A summary of the fatigue data findings is shown in Figure 9, below. Fatigue tests for the ABS master cylinder housing were done with R-values of 0.1. The maximum stress was 138 MPa, or, approximately half of the measured yield strength of the material. Minimum stress was between 13.8 and 0 MPa. The waveform of the test followed a 50-Hertz sinusoidal pattern. Run-out, or the quantity of cycles that if reached without failure signaled the end of the test, was 20,000,000 cycles.

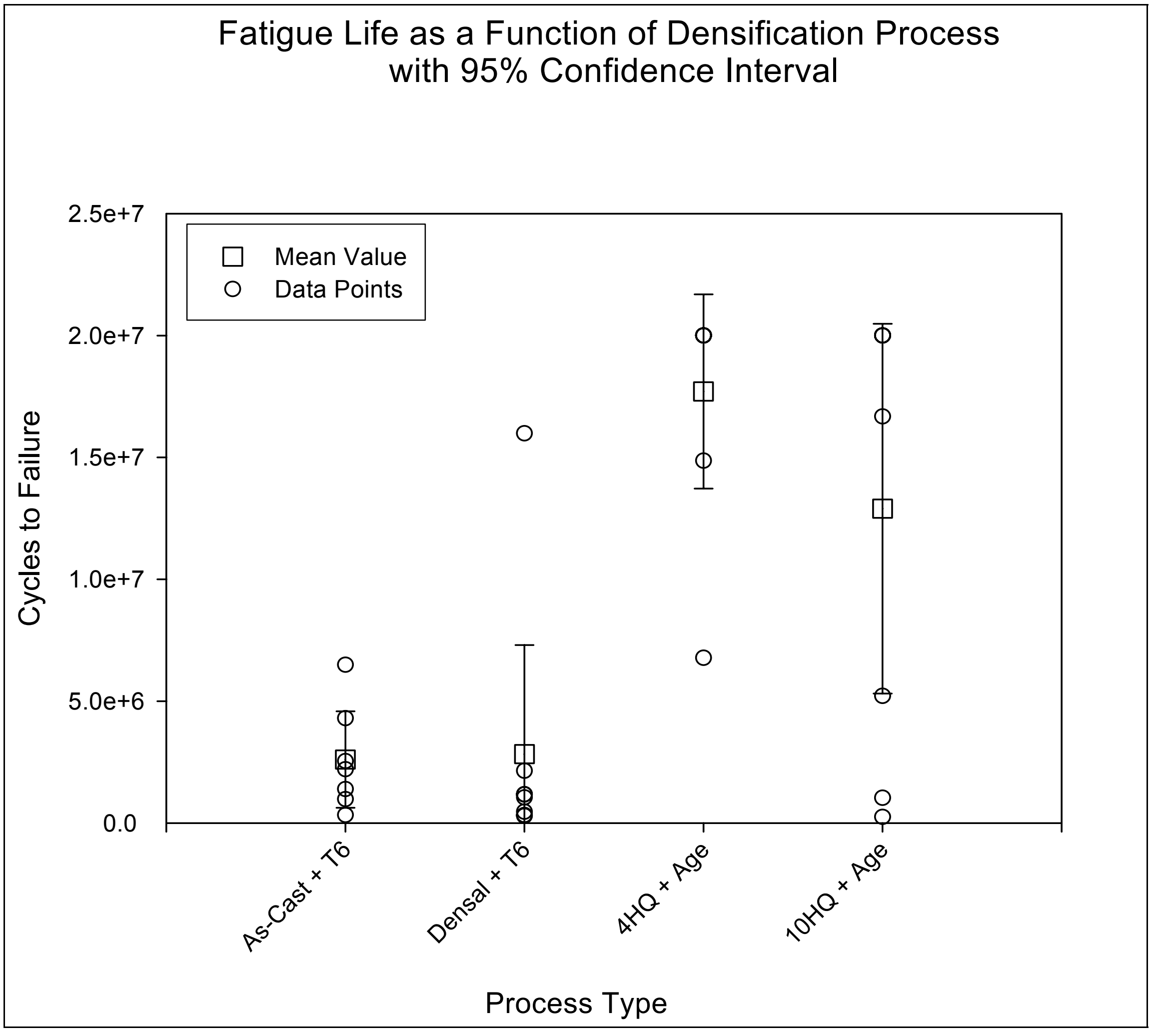


Figure 9 – Fatigue data of ABS master cylinder housing comparing processing specifications along the abscissa to cycles to failure on the ordinate axis. Data points are summarized by a calculated mean value (shown as a hollow square) and 95% confidence interval. Fatigue testing specifications are σ_{max}= 138 MPa, σ_{min}= 0 MPa, 50 Hz sinusoidal waveform.

It should be noted that all the AC- and D-group samples failed during the testing, however, several of the samples which underwent the combined processes survived the fatigue testing. Six samples in the 4HQ group and four samples in the 10HQ group are represented by their respective highest data points on Figure 8. This data is included in the calculations to determine the confidence interval and mean value included on the graph. The scatter inherent in the Figure 9 implies that more than just the porosity in the samples is steering the fatigue behavior of these castings. Subsequent fractography was necessary to further categorize the fatigue behavior.

3.2.1.4. Fractography

Optical microscopy was used to determine the point of fracture initiation on each of the fracture samples. The results of this fractography are summarized in the graph labeled Figure 10. Porosity was only apparent at the fracture initiation sites of un-HIPed samples. Significant amounts of oxide inclusion at the initiation sites appeared regardless of the processing route used in the samples. It should also be noted of Figure 10, that even in the sample group that is shown to have porosity, the As-cast group, oxides were the cause of some of the failures. This supports the theory of large amounts of oxide inclusions in the castings.

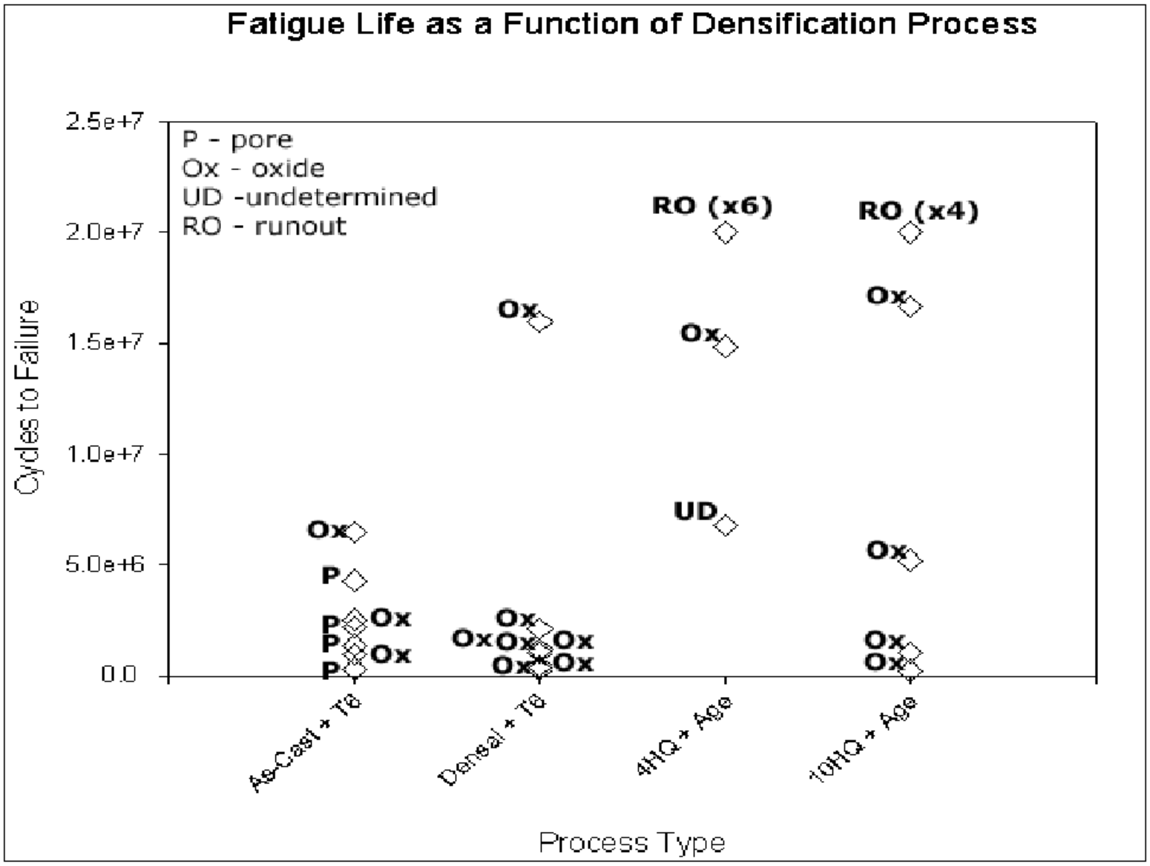
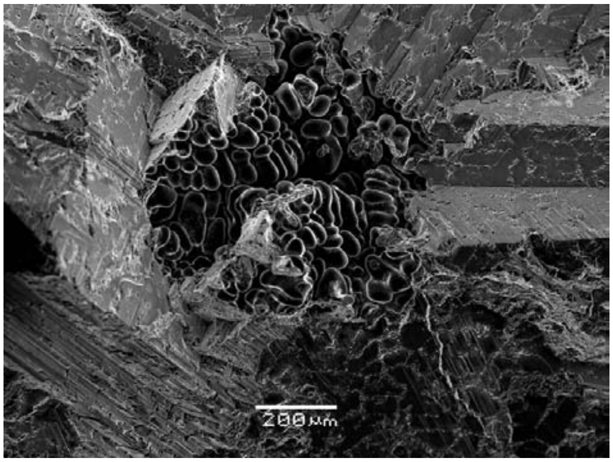
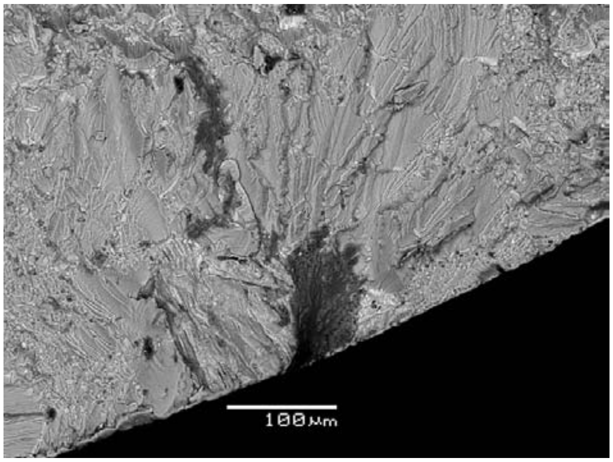


Figure 10 – Identification of the fracture initiation types superimposed on the fatigue life graph. This graph shows that whilst porosity was a factor in the fracture initiation of the un-HIPed samples, oxides played a far more predominant role in all other process types. One fracture initiation site was deemed undetermined as porosity or oxide inclusion was identified by backscatter electron imagery.

Scanning electron microscopy was used to verify the oxide inclusions in the fractography study. Examples of the are included as Figure 11a and 11b. Figure 11a represents a typical pore fracture initiation site. Figure 11b shows a backscatter electron image of an oxide inclusion at the fracture initiation site.



11a.



11b.

Figure 11a – SEM image of pore fracture initiation site, dendrites visible. Figure 11b - BEI image of oxide at fracture initiation site at edge of sample. Scale is shown on both micrographs

The fact that porosity was only present on the fracture surface of the un-HIPed samples again shows that HIP improves castings by eliminating porosity. However, the abundance of oxides on the fracture surface of the remaining samples suggests that HIP will not improve the fatigue life of *all* castings. Clearly in this study the oxides played the dominant role as the fatigue-limiting characteristic. While the lack of a difference between the D and AC process groups would also suggest that there would be little difference in the combined processed samples, this was not the case as there was a significant improvement in the fatigue life of the castings subjected to a combined process. This behavior has no explanation other than it seems the volume percent of the oxide inclusions in the D and AC groups were more than those in the 4HQ and 10 HQ groups even though the processing routes were randomly assigned to the castings. In terms of the relative fatigue life of the combined processes compared to the traditional individual processing route, little can be said. While it might seem that the combined process is more capable at improving the fatigue life of castings, this must be discounted due to the higher relative occurrence of oxides in the D process group.

3.2.2. Experimental Coupons Wedge Castings

The tensile results for the experimental coupons are show in Table VI. Labeling protocol is identical to that describe in previous sections.

3.2.2.1. Tensile Results

Table VI – Tensile results of experimental coupons, reported with average values where applicable.

Sample Designation	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Percent Elongation	Area Reduction Percent
AC2*	192.4	287.5	17.2	24.0
Average	*192.4*	*287.5*	*17.2*	*24.0*
D1	185.5	286.1	17.2	24.0
D2	188.9	288.9	17.2	23.8
Average	*187.2*	*287.5*	*17.2*	*23.9*
4HQ1	184.8	288.2	15.6	20.6
4HQ2	194.4	291.6	17.2	22.0
Average	*189.6*	*289.9*	*16.4*	*21.3*
10HQ1	196.5	295.1	17.2	21.2
10HQ2	197.2	301.3	17.2	19.2
Average	*196.8*	*298.2*	*17.2*	*20.2*

** Only one sample is reported in As-Cast (AC) condition, as there was an error in testing.*

The tensile results for the Sr-modified A356 experimental coupons show once again no significant variation in the tensile results as a function of processing route. It should be noted that the level of ductility for this sample seems abnormally high by comparison to published values [13].

3.2.3. Commercially Produced Steering Knuckle

3.2.3.1. Tensile Results

Shown below, as Table VII are the tensile results for the steering knuckle experiment. Average values are calculated for all properties.

Table VII – Tensile results of sand-cast, Sr-modified A356 steering knuckle, reported with average values where applicable.

Sample Designation	0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Percent Elongation	Area Reduction Percent
AC1	*	192.0	0.3	0.4
AC2	*	217.7	0.5	0.6
AC3	*	178.6	0.3	0.2
Average	*	*196.1*	*0.4*	*0.4*
D1	248.9	274.0	1.3	1.8
D2	250.6	263.9	0.7	1.2
D3	249.6	266.9	0.9	0.6
Average	*249.7*	*268.3*	*1.0*	*1.2*
4HQ1	210.9	241.0	1.2	2.6
4HQ2	225.1	252.3	1.2	2.6
4HQ3	212.8	243.2	1.5	2.0
Average	*216.3*	*245.5*	*1.3*	*2.4*
10HQ1	223.3	252.7	1.3	1.8
10HQ2	204.8	250.2	2.0	2.6
10HQ3	212.5	250.3	2.0	2.3
Average	*213.5*	*251.1*	*1.8*	*2.2*

** Yield strength in As-Cast (AC) condition, were deemed erroneous by testing facility and hence not reported.*

As with the two previous studies the difference in the strength and ductility for these castings as a function of the processing route in negligible. It should be noted in this case that the ductility of all these samples is notably lower than the published standards [13]. Furthermore, the AC process group, which was commercially heat treated displays the lowest values of ductility.

3.2.3.2. Fatigue Results

The fatigue results for these samples are shown as Figure 12. The testing specifications used for this round of testing allowed the results to be presented in S-N form. The data are presented in this manner because the amount of samples allowed for fatigue testing with various stress levels. The two previous studies were done with significantly fewer sample castings. Stress level is noted on the graph. The waveform of the testing was 50 Hertz sinusoidal with an R-ratio of -1.0.

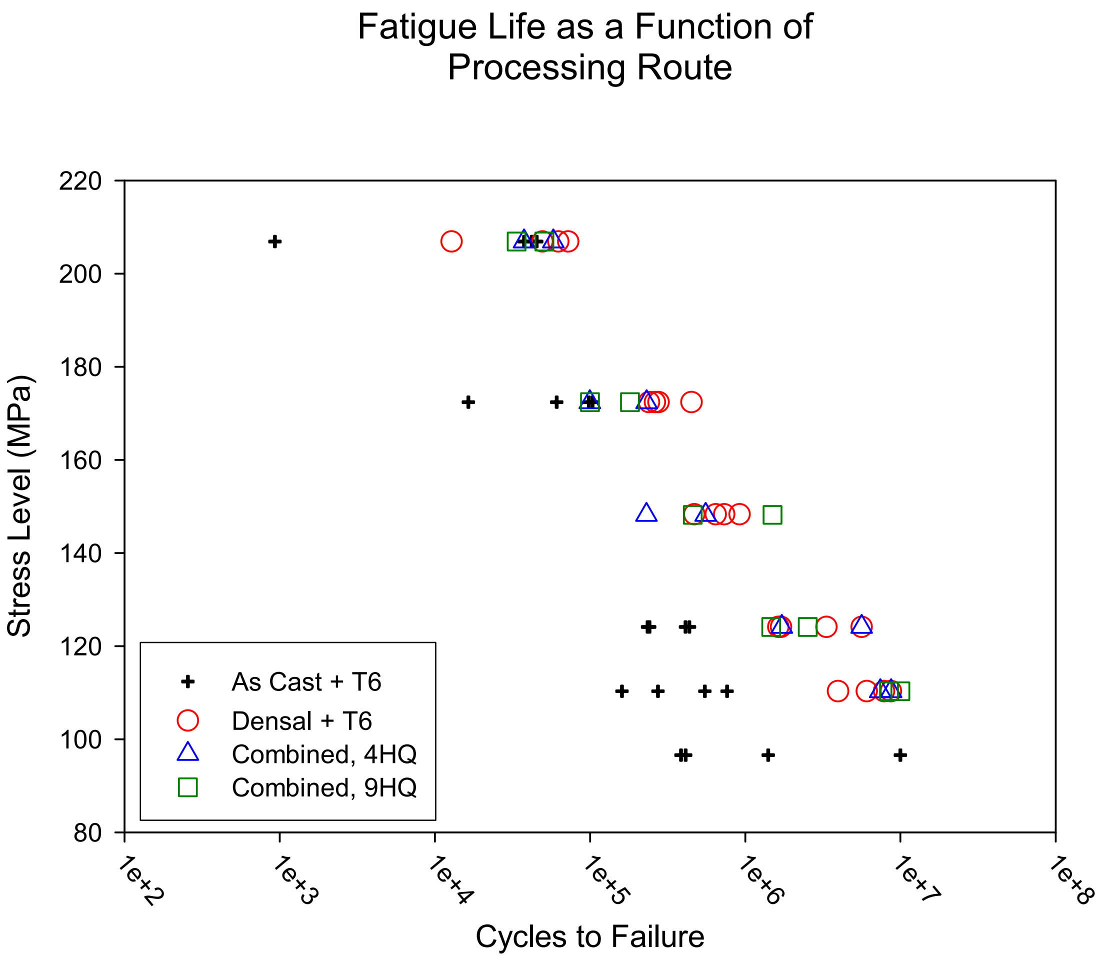


Figure 12 – Fatigue data of sand-cast Sr-modified A356 steering knuckles. Data is presented in S-N format. Test frequency was 50 Hertz. R-ratio for tests equals –1.0.

This round of testing conforms more regularly with previously held beliefs on the effect of HIP on the fatigue properties of aluminum castings. It should be noted that there is an order of magnitude increase in fatigue life of the HIPed samples (both those which were independently processed, and those subjected to the combined process) at the lower stress levels (~115MPa). There is much less difference as the stress level approaches the yield strength of the alloy (~210 MPa) which is to be expected. It would also seem that the variance in the HIPed samples is much smaller than the variance in the un-HIPed samples. Furthermore there is no appreciable difference between the fatigue performance of the samples that were traditionally densified and heat treated and those that were processed with the combined methodology.

4. Conclusions

4.1. Process Combination Feasibility

Clearly the possibility of continuing on to the mechanical property evaluation portion of this experiment depended on the successful implementation of the experimental procedure. It was shown experimentally in this study that maintaining solutionizing temperature during the venting portion of the HIP cycle is possible. Furthermore, it is likely that the energy required to maintain $T_{solution}$ during depressurization is proportional to the amount of gas in the vessel due to the adiabatic expansion of the gas. This would mean that as the load size increases the power required to maintain temperature is reduced. Hence, this experiment, with only one casting processed, actually used the most power and as the casting load increases to the capacity of the vessel, maintaining $T_{solution}$ will likely become easier.

The measured quench delay for the experimental process also proved short enough for the continued process evaluation.

4.2. Mechanical Property Evaluation

- Tensile results of all the experiments conducted prove that the combined Densal®/solution heat treat process produces casting with similar tensile properties to castings processed with the standard methods. This proves that elevated pressure has no detrimental effect on the tensile properties of the castings tested here. In terms of resultant tensile properties, a combined Densal®/solution heat treat process is feasible.

- Fatigue results in the study of the ABS master cylinder housing prove that oxide inclusions can play a major role in crack initiation. In comparison to previous research the presence of oxides in the samples appear to mask the beneficial effect of HIP densification [2,4-6]. However, the fatigue data of both combined processes seem to mirror previously held theories of the effect of HIP on the fatigue life of castings. Both of the combined Densal® + solution heat treating processes yielded fatigue properties that were significantly better than those of as-cast + T6 samples. Also, in the scope of this experimental run, savings in both process time and energy were realized by combining the processes.
- In viewing the fatigue results of the sand-cast, Sr-modified A356 steering knuckle, an improvement in fatigue strength after Densal® is readily apparent when compared to non-HIPed samples. Therefore, it is possible to make a direct comparison between the combined processes and the standard methods in the production of critical application aluminum castings. It is therefore concluded, that the parts subjected to the combined process show no appreciable difference in fatigue strength when compared to parts produced by the standard Densal® + T6 process. Saving in both time and energy over the traditional methods were incurred by using the combined process. These results warrant further investigation into the implementation of a commercial combined Densal®/solution heat treat process.

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Theoretical modeling of energy savings incurred from the use of a combined Densal®/solution heat treatment for cast aluminum alloys

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Abstract

Previous work by the authors has shown that the combined process of HIP/Densal® and solution heat treatment effectively mimics the microstructure and mechanical properties of the current, individual processes of HIP/Densal® and subsequent solution heat treatment. This paper evaluates the energy consumption of the combined process and the two independent processes. Thermodynamic calculations revealed that the energy consumed by the combined process for a typically loaded HIP vessel is fifty percent less than the energy required to process the same quantity of castings with the two individual processes. However, it was determined that a critical ratio of the volume occupied in the HIP vessel by castings to the total HIP vessel volume exists that ultimately determines the efficiency of the combined process. This critical ratio was calculated to be approximately fifteen percent. If the volume ratio is less than fifteen percent then the combined process is less energy efficient then conventional processing. These thermodynamic calculations were experimentally verified with power consumption process data in a production facility. In addition, the time required for the combined process of HIP/Densal® and solution heat treatment was thirty percent less than the conventional two-step process.

1. Introduction

Hot isostatic pressing (HIP) is used in industry to eliminate porosity in castings [1,2]. HIP uses elevated temperature and pressure to hydrostatically compress castings and eliminate pores through plastic deformation and diffusional creep mechanisms [1-2]. The elimination of porosity in castings leads to increased fatigue life, ductility and impact toughness [3-7]. While the advantages of using the HIP process are clear, it is still an independent process that adds time and energy costs to the production of critical application castings. The first step in the cost reduction of the HIP process for aluminum castings was the Densal® process. Densal® is a Bodycote proprietary densification process tailored specifically for the elimination of porosity in critical applications aluminum castings [6]. It is speculated that further time and energy savings could be realized through additional integration of the Densal® process into the manufacturing procedure of aluminum castings.

One method of integrating Densal® into the manufacturing process is to combine it with the subsequent heat treating steps that are necessary to attain desired tensile properties. A typical T6 heat treatment of A356 aluminum, according to ASM [8] includes an 8-12 hour solutionizing soak at 540°C to homogenize the alloy and create a saturated solid solution of the alloying constituents. Next, to form a supersaturation of the alloying constituents, a rapid quench is employed. Finally, an aging step of 3-5 hours at 155°C is used to obtain optimal tensile properties [8-10]. Due to similarities in the solutionizing temperature of most aluminum alloys and the dwell temperature of the Densal® process, a process combination is appropriate. Experimental work completed by the author shows that a combined process is viable in terms of the resultant mechanical properties of the castings tested. In fact, the work completed shows no difference between the tensile and fatigue properties of the castings processed by the combined Densal®/solution heat treatment process or the independent Densal® and solution heat treatment processes [7]. Shown as Figure 1 are S-N data points comparing the fatigue behavior of castings subjected to combined Densal®/solution heat processes, and castings subjected independent Densal® and heat treatment. The fatigue behavior of castings that were not subjected to a HIP process is also included in the graph. The difference between the castings subjected to either of the combined processes and the independent process is negligible. It should be noted that the difference in fatigue life between the un-HIPed samples and the HIPed samples is nearly an order of magnitude in the most extreme cases.

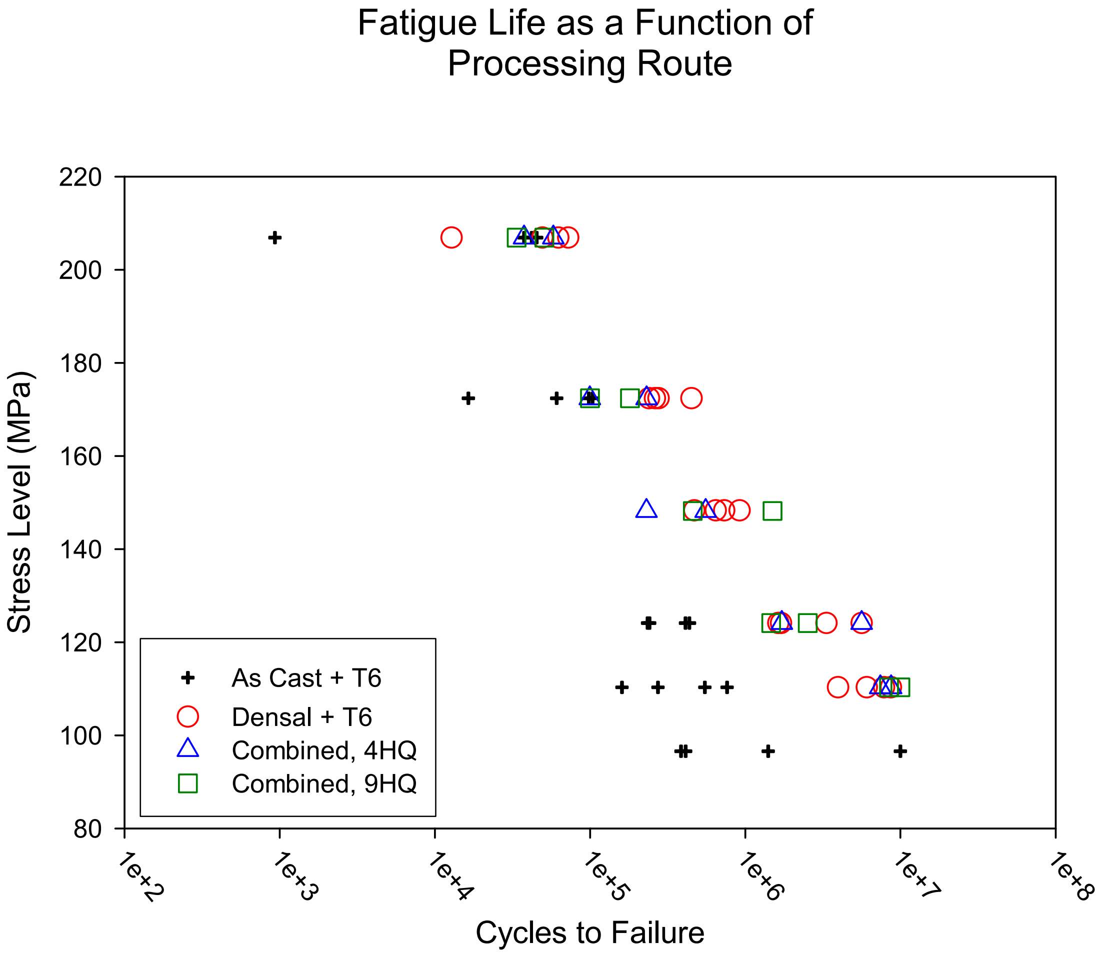

Figure 1 – Verification of fatigue results from previous study. Graph shows no difference in fatigue behavior between castings subjected to the independent processes of Densal® followed by T6 heat treatment (labeled "Densal + T6") and castings subjected to the combined process of Densal®/solution heat treatment followed by aging ("Combined, 4HQ" and "Combined, 9HQ"). It should be noted that there is a marked improvement in the fatigue behavior of all the densified samples compared to the un-HIPed samples ("As Cast + T6"). The two different combined processes, 4HQ and 9HQ, are different from each other in the length of time spent at solution temperature, which were four hours and nine hours, respectively.

The thermal profile of the combined process is shown in comparison to the thermal profile of the two independent processes as Figure 2. The profiles show the basic premise behind the process combination: The combined process uses the time spent at HIP dwell temperature as part of the solutionizing dwell time. The castings are then water quenched from the HIP vessel. More details on the design of the experimental process can be seen in citation [7]. Figure 2 also shows the time savings incurred by the use of the combined process. It is estimated that the time from mold to service for the combined process is seventy percent of the time required for the independent processes.

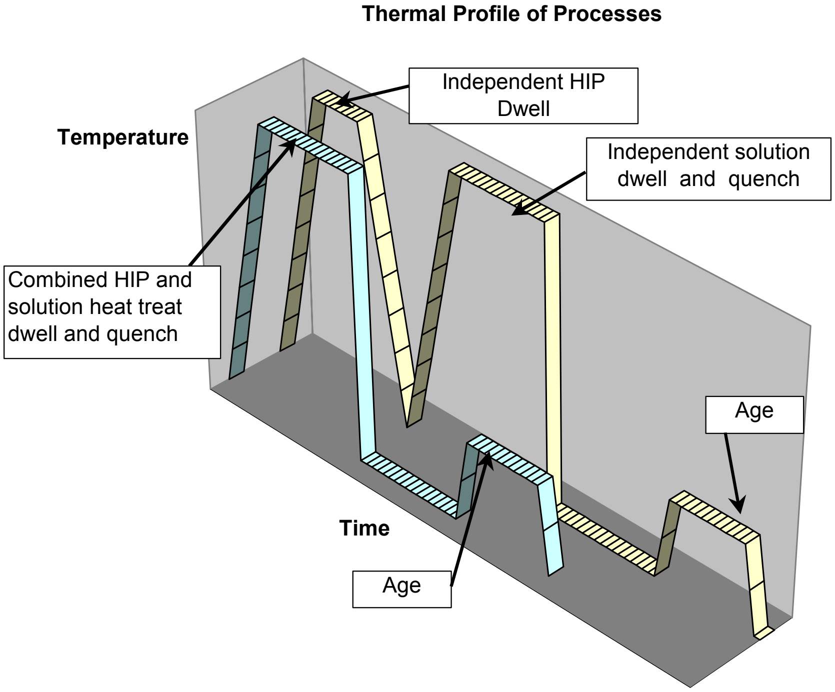

Figure 2 – Thermal profiles of experimental samples subjected to the combined Densal®/ solution heat treat process (foreground) the independent processes of Densal® and T6 treatment (background). This graph shows significant time savings by using the combined process. It indicate that the combined process is completed approximately 30% quicker than the independent processes assuming no time between the end of Densal® process and the start of the solution heat treatment for the castings produced with the conventional independent process. Units are omitted from the graph to preserve Bodycote PLC proprietary specifications.

The purpose of this paper is to present the theoretical work done in modeling the energy consumption of the combined Densal®/solution heat treatment process. These data calculations will be compared to the energy consumption of the conventional, independent processes. Experimental data will be used to verify the results of the theoretical modeling.

2. Procedure

2.1. Theoretical Framework

2.1.1. Identification of Energy Consumption

In order to compare the energy consumption of the two processing routes being examined, it is necessary to first understand all the thermal and mechanical energies involved with the processes. This will be accomplished by modeling castings and where appropriate, their surrounding gas media, as a thermodynamic system. This system will be examined as it passes through the different process routes.

Let the heat transferred into the system be defined as Q, and the mechanical work done by the pressurizing media in the system be defined as W. If, for example, the gaseous media is allowed to expand and depressurize, the system does negative work, conversely, if the gas is compressed, positive work is done.

Conventional processing starts with the HIP cycle, which heats and pressurizes the system, $+Q$ and $+W$. Heat is constantly added into the system via furnace power during the tenure of the HIP dwell portion due to energy losses into the HIP vessel walls, etc. but the pressure is not subject to much change as little of the mechanical energy is lost. After the dwell portion of the HIP cycle, the pressurized gas is vented and the system is cooled, -*Q,* and -*W*. The heat treatment cycle commences with the application of thermal energy, +*Q,* to the system until the solutionizing temperature, $T_{solution}$, is reached. $T_{solution}$ is maintained for a given time and the heat is rapidly removed from the system via a water quench, -*Q*. The energy transfer in the aging step mimics that of the solution step less the quench, i.e. gradual heat gain, +*Q,* followed by gradual heat loss, -*Q*.

In the combined process, again thermal and mechanical energies are added to the system at the start of the HIP cycle. During the depressurization step, expanding gas again performs negative work on the system (-*W*), which, if left unabated would lead to cooling within the system via adiabatic expansion of the gas. To overcome this, heat is added to the system to maintain $T_{solution}$ (+*Q*). This heat remains in the system until the quench step. The other steps in the process are identical to those described above.

This relationship between temperature, pressure and thermal and mechanical energies are shown schematically for the individual processing method as Figure 3. Figure 4 shows the same relationship for the combined process. These graphs are a simplification of the actual heating processes as heat is lost from the system continuously and therefore requires constant minute energy adjustments to maintain both HIP and solutionizing dwell temperatures. It is however assumed that these adjustments will be roughly equivalent between both the combined process and the individual process methods of production and therefore these adjustments are ignored.

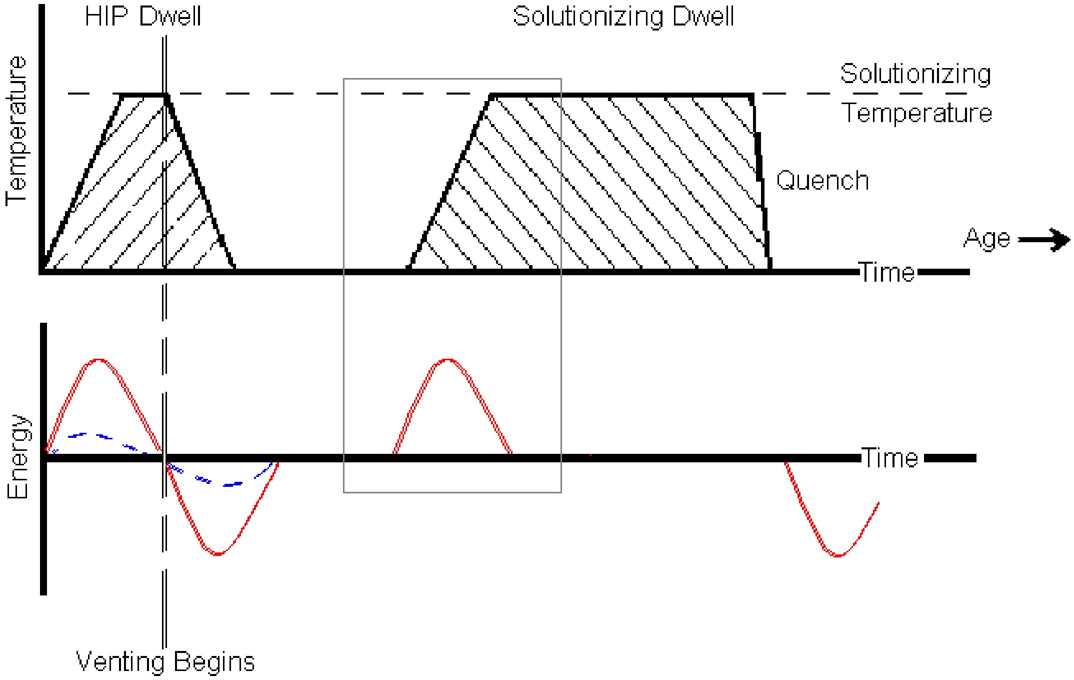

Figure 3 – Schematic detail of the energy consumed by the individual processes of Densal® and solution heat treatment (the aging process is not shown on this graph). The top portion of the graph shows the thermal profile of a casting subjected to the individual processes, temperature versus time. The bottom portion shows the corresponding thermal energy requirements (solid line) as well as the mechanical work done on the system (dashed line). The boxed area represents the area of interest in terms of the thermal energy comparison to the combined process.

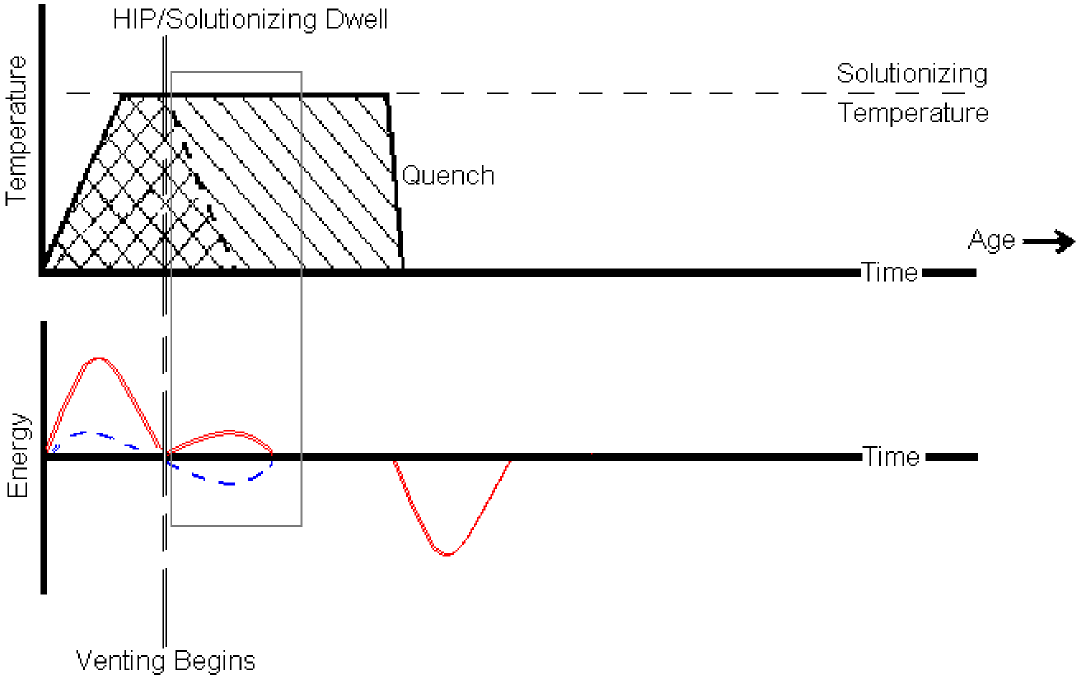

Figure 4 – Schematic detail of the energy consumed by the combined Densal®/solution heat treatment. The top portion of the graph shows the thermal profile of a casting subjected to the combined process, temperature versus time. The bottom portion shows the corresponding thermal (solid line) and mechanical (dashed line) energy requirements. The boxed area represents the region of interest in the thermal modeling. The curves included in the boxed area represent the thermal energy (solid) required to overcome the adiabatic cooling work (dashed) done by the gas on the system.

It should be noted of the bottom portions of Figures 3 and 4, that any line below the abscissa represents a negative energy. Therefore the negative work done by the depressurization is shown below this axis, as is the thermal energy removed from the system during the quench.

If all the steps that are identical in the two processing routes are discounted, it becomes clear that there are only two necessary comparison points to determine the difference in process efficiency. The heat up portion of the solution heat treatment in the individual processes, and the temperature maintenance step during the depressurization of the combined process are all that need to be compared. These portions are shown as the boxed in area in Figures 3 and 4.

2.1.2. Calculations

2.1.2.1. Individual Process Calculations

To calculate the amount of energy required to raise a casting from room temperature, $T_{ambient}$, to solution temperature, $T_{solution}$, as would be the case when solution heat treating a casting in the conventional independent process, requires using the following formula:

$$E = mc_p \Delta T \qquad \text{[eq. 1]}$$

Where, E is the total energy required to raise the system of a casting being modeled with mass m, and specific heat c_p, from $T_{ambient}$ to $T_{solution}$, represented as ΔT.

2.1.2.2. Combined Processes Calculations

Pressurized gas in the HIP vessel complicates the modeling of the energy requirements for the combined process, as it adds another component to the thermodynamic system that cannot be neglected. This is because gas undergoing pressure changes does work on the casting in the system. Fortunately, experiments completed to date [7] have shown that there is no difference in the temperature of the gaseous pressurizing media in the HIP vessel and the castings that are in contact with the gas. This is a due to the high heat transfer rate between the castings and the gas that results from the elevated pressure in the HIP vessel. The heat transfer coefficient between the castings and the gas at the pressures involved in this process is on the order of 100 W/m^2 K [11]. Therefore it can be stated correctly that the temperature of the gas and the castings within a HIP cycle are identical. Furthermore, it is reasonable to assume all that is required to calculate the energy needed to maintain $T_{solution}$ in the casting is to calculate the energy required to maintain $T_{solution}$ in the gas. The governing equation for the system being modeled in the HIP vessel is the *First Law of Thermodynamics*, which states:

$$Q = u_2 - u_1 + W \qquad \text{[eq. 2]}$$

Where, Q, represents the amount of heat transferred into the system to maintain $T_{solution}$, u_1 and u_2 represent the internal energy of the gas at maximum and minimum pressure, respectively, and W, represents the work done by the expanding gas as pressure is vented. By design, this system is isothermal, that is, during the depressurization of the HIP vessel, heat is added to maintain $T_{solution}$ and consequently there is no change in temperature. Internal energy of any gas is only a function of temperature, therefore it can be concluded that there is no change between u_1 and u_2, and therefore equation 2 is simplified to:

$$Q = W \qquad \text{[eq. 3]}$$

This basically states that the heat required to maintain $T_{solution}$ is equal in magnitude to the work done by the expanding gas. In the case of an ideal gas, this value is a relatively simple computation of:

$$W = -\int_{v_1}^{v_2} P dv \qquad \text{[eq. 4]}$$

Where v_1, v_2 are the specific volumes of the gas at maximum and minimum pressure respectively, and P is the starting pressure of the nitrogen gas. When combined with Boyle's law of ideal gases, Equation 4 takes on the form:

$$W = -\overline{R}T\int_{v_1}^{v_2}\frac{dv}{v} = -\overline{R}T\ln\frac{v_2}{v_1}m \qquad \text{[eq. 5]}$$

Where $\overline{R}$ represents the gas constant of nitrogen (universal gas constant divided by the molecular weight of nitrogen), T represents the isothermal temperature, and m is the mass of the gas involved. Equation 5 will be used to determine the amount of energy required to maintain $T_{solution}$. This value will be directly compared to the energy requirement calculated for the solution heat treatment step for the individual processes.

The major assumption made in these calculations is that the temperature within the HIP vessel is uniform during the venting process.

2.2. Experimental Verification of Modeling

A casting subjected to a combined HIP/solution heat treat process was instrumented with Type-K thermocouples in order to verify the theoretical calculations of process energy consumption. The casting chosen for this test was a commercially produced, permanent mold, Al-Si-Mg automotive ABS master cylinder housing. This casting is approximately 1kg in mass and 150mm by 150mm by 30mm in dimensions with a relatively high surface area-to-volume ratio. The purpose of choosing a casting with a high surface area-to-volume ratio was that this casting represents a “worst case scenario” of retaining heat during depressurization. The chemical composition of the ABS master cylinder housing, determined through Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES), is given in Table I.

Table I - Chemical composition of Al-Si-Mg ABS master cylinder housing casting determined via ICP-AES. Values are the averages of five readings performed on two different castings (ten total readings). The standard deviations for the calculations are included to show statistical variance in data.

	Si	*Mg*	*Fe*	*Ti*	*Sr*	*Cu, Mn, Ni, Zn*
Average Weight %	6.77	0.88	0.14	0.099	0.009	<0.035
Standard Deviation	0.118	0.022	<0.005	<0.003	0.000	<0.005

To show the relative complexity of the casting used, a sectioned view is included as Figure 5 below. Two thermocouples were used to record the thermal profile of the casting in the initial experiments and their location in the part is shown in Figure 5. The location of one thermocouple (TC) is marked in the three views with an “+”. This TC measured the center temperature of the casting. The second TC, which is marked with an “o” in the figure, records the “skin” temperature of the casting.

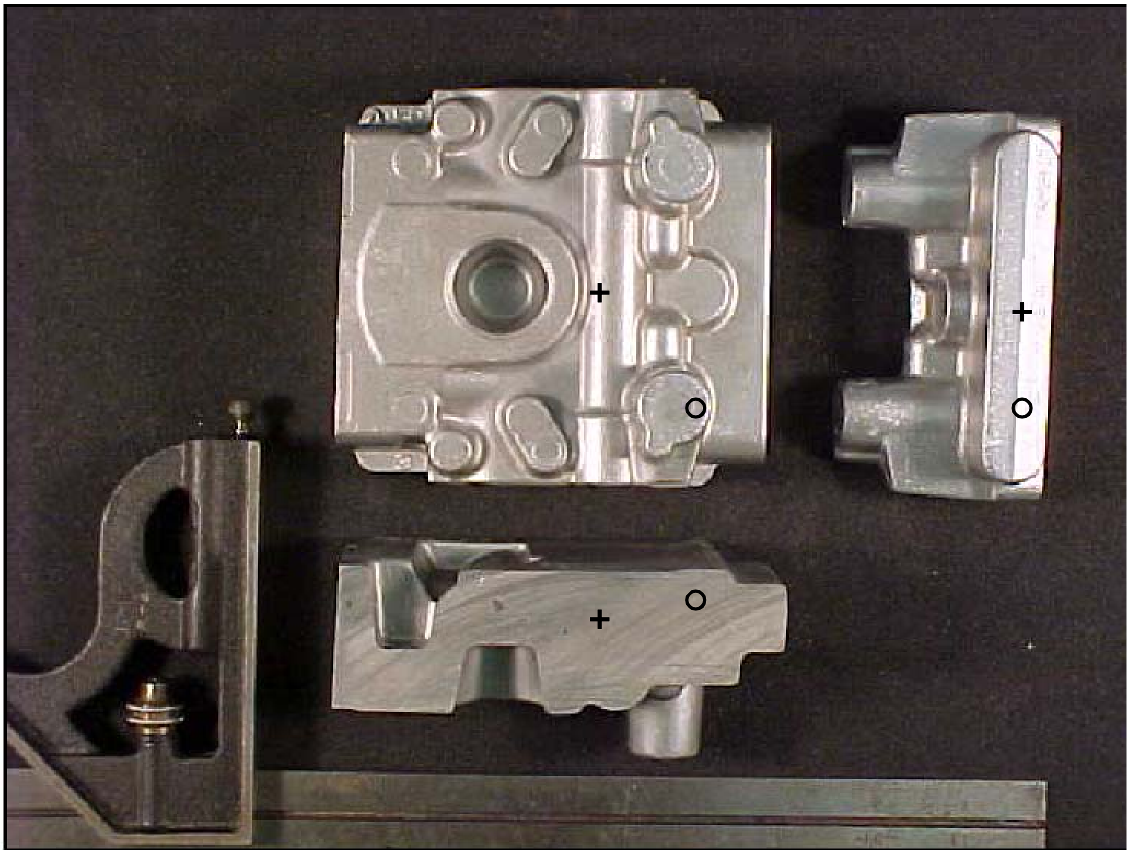

Figure 5 – Sectioned ABS master cylinder housing used in initial experiments. Location of two thermocouples marked in all views with + and o. (12-inch rule included to show scale)

The HIP vessel used was an ABB model at Bodycote IMT, Inc., in Princeton, KY. The working height and diameter of the HIP vessel are respectively 305mm and 205mm. Nitrogen gas was used as the HIP media. Type-K TCs were used to instrument the castings. Readings of temperature, pressure and furnace power were logged every two-minutes. Time, temperature and pressure of the run followed the Densal® proprietary specifications. For this study, the maximum gas vent rate that allowed the casting skin temperature to remain above $T_{solution}$ was used. The pressure vent rate used was calculated as approximately 0.5 MPa/minute.

3. Discussion and Results

3.1. *Theoretical Modeling*

The physical and thermal properties of the casting modeled are shown in Table II. The amount of energy required to raise the temperature of a casting from $T_{ambient}$ to $T_{solution}$ for these parameters as well as the amount of energy required to maintain $T_{solution}$ in the combined process are also shown in Table II.

Table II – Physical and thermal properties of single casting modeled. Calculated energy requirements of attaining $T_{solution}$ during heat treatment as well as energy required to maintain $T_{solution}$ during combined process venting are shown in bold.

	Property Value	**Property Units**
Mass of casting	1.00	Kg
Specific heat of casting	~900	J/kg-K
$T_{solution} - T_{ambient}$, ΔT	475	K
Energy elevate casting to $T_{solution}$ during heat treatment	**~430**	**kJ**
Volume of HIP vessel	0.01	m^3
Total volume of casting	0.0004	m^3
Gas constant for N_2, R	296804.39	J/kg-K
Maximum gas pressure, P_1	35.0	MPa
Minimum gas pressure, P_2	0.1	MPa
Specific volume of N_2 at P_1	6.55	m^3/kg
Specific volume of N_2 at P_2	2294.29	m^3/kg
Mass of N_2 at P_1	0.0015	Kg
Energy required to maintain $T_{solution}$ during combined process	**~2000**	**kJ**

It is clear from this fundamental calculation that the combined process is actually *less* efficient in terms of energy consumption than the independent processes. This appears to contradict intuition, as it would seem that the combined process would be the more efficient process. However, the ability of the HIP vessel to maintain $T_{solution}$ during venting relies on the fact that the vessel is nearly completely occupied, not by the pressurized gas, but by the castings being processed. In this calculation, the ratio of the volume occupied by the casting to the overall HIP vessel volume is quite low. If the same calculations are done with a higher percentage of the HIP vessel volume consumed by the castings the figures are quite different. This data is shown in Table III below.

Table III – Physical and thermal properties of multiple castings modeled. Calculated energy requirements of attaining $T_{solution}$ during heat treatment as well as energy required to maintain $T_{solution}$ during combined process venting for seven castings are again show in bold.

	Property Value	Property Units
Mass of casting	7.00	Kg
Specific heat of casting	~900	J/kg-K
$T_{solution} - T_{ambient}$, ΔT	475	K
Energy elevate casting to $T_{solution}$ during heat treatment	**~2800**	**kJ**
Volume of HIP vessel	0.01	m^3
Total volume of casting	0.0028	m^3
Gas constant for N_2, R	296804.39	J/kg-K
Maximum gas pressure, P_1	35.0	MPa
Minimum gas pressure, P_2	0.1	MPa
Specific volume of N_2 at P_1	6.55	m^3/kg
Specific volume of N_2 at P_2	2294.29	m^3/kg
Mass of N_2 at P_1	0.0011	Kg
Energy required to maintain $T_{solution}$ during combined process	**~1500**	**kJ**

Clearly, it can be concluded that the volume percent of the HIP vessel that is occupied by castings has a significant impact on the efficiency of the combined process. Figure 6, further illustrates this point. This graph shows the relationship between the number of castings being processes and the theoretical energy required to complete the specified process.

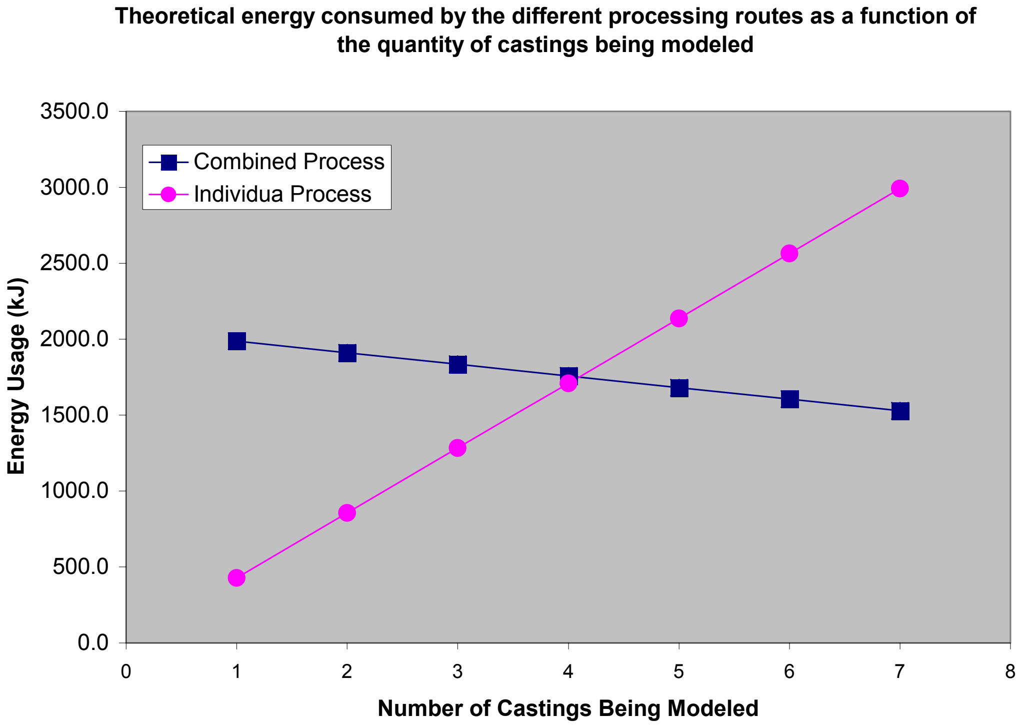

Figure 6 – Theoretical energy required to maintain $T_{solution}$ in the combined process, and attain $T_{solution}$ in the conventional process as a function of the quantity of castings being modeled. This graph clearly shows the amount of energy consumed by the maintenance of $T_{solution}$ in the combined process is inversely related to the amount of castings processed.

Therefore, a ratio of casting volume to HIP vessel volume exists that defines the level of efficiency that is attainable through the combined process. The same graph in Figure 6 is presented as Figure 7 with the abscissa showing the volume percentage of the HIP vessel occupied by castings. Figure 7 shows that for a given HIP vessel a minimum level of castings must be determined to use the combined process in an energy efficient manner. For this example, calculations indicate that the value of this "efficiency ratio" equals approximately fifteen percent.

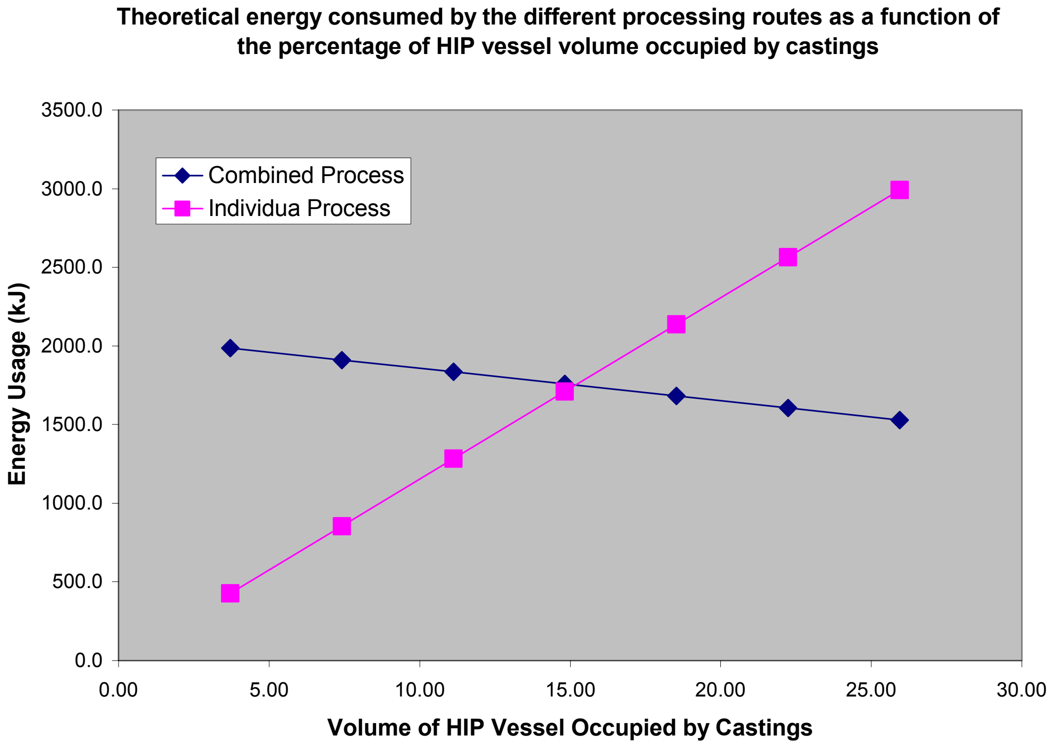

Figure 7 – Theoretical energy required to maintain $T_{solution}$ in the combined process, and attain $T_{solution}$ in the conventional process as a function of the volume percent of the castings being modeled over the total HIP volume. The quantity of castings required to attain a greater energy efficiency in the combined process versus the individual process is the quantity of castings that equals greater then fifteen percent of the HIP vessel volume, i.e. five castings.

Therefore, in order for a combined process to be more energy efficient than the individual processes, the HIP vessel must be at least fifteen percent occupied by castings. For comparison, if only one casting is processed in the vessel as was originally calculated, the casting volume-to HIP vessel volume ratio is 0.04, or four percent of the vessel is occupied by the casting.

According to the calculations done here it has been showed that a combined process done with a “fully loaded” HIP vessel can be nearly twice as energy efficient as the independent cycle. Conversely the process can also be half as energy efficient in the case of a “under loaded” vessel.

3.2. Experimental Verification

Figure 8 shows a graph of casting temperature, gas pressure and HIP furnace power as a function of time for the combined HIP/solution heat treat run. As was proven in the theoretical calculations previously reported, the graph shows the impact of venting at constant temperature on furnace power as a significant increase in the power requirement to maintain $T_{solution}$ during depressurization. Note that the power peak during the pressure venting process consumes more energy, i.e. contains more area beneath it, than the initial ramp up portion of the cycle.

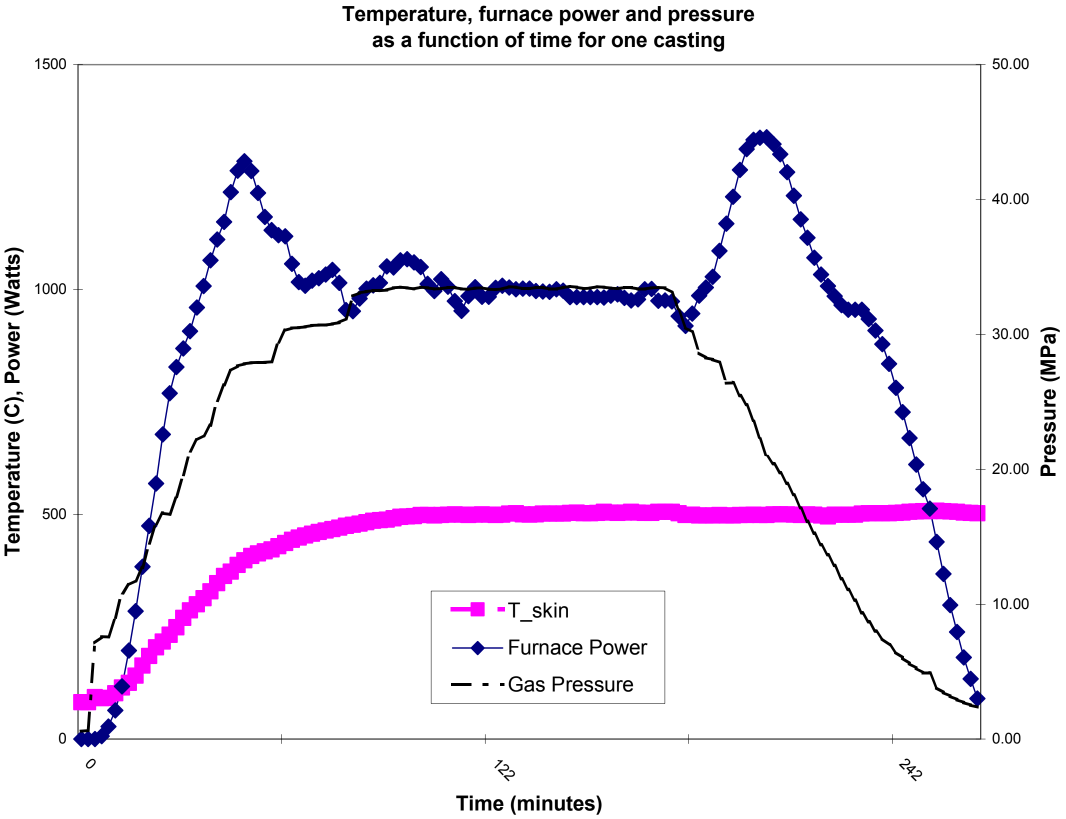

Figure 8 – Graph showing the relationship between pressure and furnace power as casting temperature remains constant during venting. Pressure vent rate is roughly constant (~0.5MPa/minute). HIP vessel contains one instrumented casting (mass=~1 kg). It should be noted that T_skin, shown near the bottom of the graph as a solid line, is maintained during the depressurization step, but this maintenance is at the significant cost of furnace power (represented by the line marked with diamond symbols).

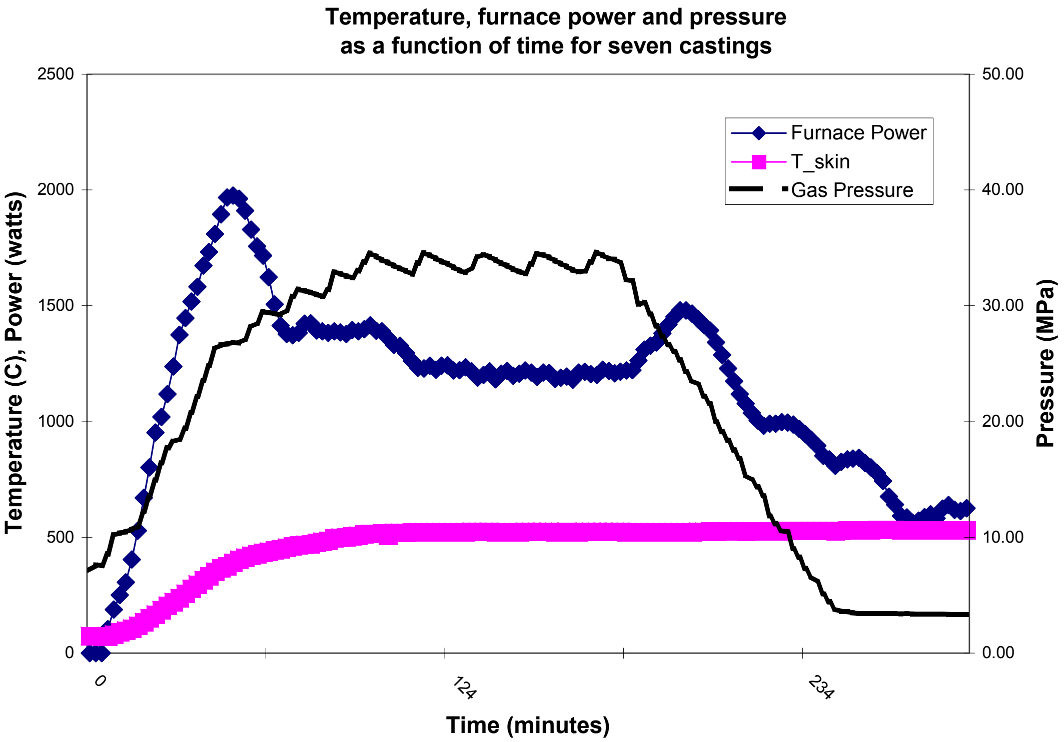

Figure 9 – Graph showing the relationship between HIP pressure and furnace power as casting temperature remains constant during venting. Pressure vent rate is roughly constant (~0.5MPa/minute). HIP vessel contains one instrumented casting and six sample castings (total mass = ~7 kg). As is expected, the overall power consumed by the process is more than that in the previous example. T_skin, shown as the thick line near the bottom of the graph, is again maintained during the depressurization step and the amount of energy needed to maintain this temperature during venting is comparatively small.

Figure 9 presents a graph of constant temperature venting with a load in the HIP vessel of seven castings (one instrumented casting and casting six castings being processed). This data demonstrates that because the aluminum castings occupy more of the vessel volume (~4% versus ~28%), and consequently less gas is present, the impact of venting at constant temperature on furnace power is significantly decreased by comparison to the previous data. Compared to the initial heat-up portion of this cycle, the second power peak, which occurs during the pressure-venting portion of the cycle, is relatively low.

This experimental data supports the theoretical modeling conclusion that process energy efficiency increases with the volume occupied by castings in the HIP vessel.

4. Conclusions

- The combined process of Densal® and solution heat treatment has the potential for saving as much as thirty-percent in process time when compared to the independent processes. This figure does not however take into account the transit time between HIP and heat treatment facilities that most castings that are currently HIPed are subjected to. If this time is incorporated into the calculations even greater savings in mold-to-service times could be expected.
- It has been proven that the combined process is not always more energy efficient than the alternative independent Densal® and solution heat treat processes. In fact a ratio of casting volume being processed-to-HIP vessel volume exists that determines whether or not the combined process is more energy efficient than the independent processes. If the volume of castings within the vessel is sufficiently in comparison to the total HIP vessel volume small (less than fifteen percent), the energy required to overcome the cooling which results from the adiabatic gas expansion makes the combined process less energy efficient than the independent process.
- However, the desire to achieve maximum process efficiency dictates that most HIP cycles are run at full vessel capacity, so the likelihood of a partially loaded HIP vessel can be discounted. In the worse case scenario of loading the HIP vessel to maximize subsequent quench rates, the casting volume-to-vessel volume would still be sufficiently high to ensure energy savings [8]. Therefore, allowing that the volume

percent of castings in the HIP vessel will always be greater than the threshold value suggested herein, the combined process, even conservatively estimated could increase energy efficiency of the densification/heat treat portion of the production of critical application aluminum castings by as much as fifty percent.

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5. Conclusions

- Tensile results of all the experiments conducted prove that the combined Densal®/solution heat treat process produces casting with similar tensile properties to castings processed with the standard methods. This proves that elevated pressure has no detrimental effect on the tensile properties of the castings tested here. In terms of resultant tensile properties, a combined Densal®/solution heat treat process is feasible.
- Fatigue results in the study of the ABS master cylinder housing prove that oxide inclusions can play a major role in crack initiation. In comparison to previous research the presence of oxides in the samples appear to mask the beneficial effect of HIP densification. However, the fatigue data of both combined processes seem to mirror previously held theories of the effect of HIP on the fatigue life of castings. Both of the combined Densal® + solution heat treating processes yielded fatigue properties that were significantly better than those of as-cast + T6 samples. Also, in the scope of this experimental run, savings in both process time and energy were realized by combining the processes.
- In viewing the fatigue results of the sand-cast, Sr-modified A356 steering knuckle, an improvement in fatigue strength after Densal® is readily apparent when compared to non-HIPed samples. Therefore, it is possible to make a direct comparison between the combined processes and the standard methods in the production of critical application aluminum castings. It is therefore concluded, that the parts subjected to the combined process show no appreciable difference in fatigue strength when compared to parts produced by the standard Densal® + T6 process. Saving in both time and energy over the traditional methods were incurred by using the combined process.

- Modeling the time expense proves that the combined process of Densal® and solution heat treatment has the potential for saving as much as thirty-percent in process time when compared to the independent processes. This figure does not however take into account the transit time between HIP and heat treatment facilities that most castings that are currently HIPed are subjected to. If this time is incorporated into the calculations even greater savings in mold-to-service times could be expected.
- Theoretical modeling has also proven that the combined process is not always more energy efficient than the alternative independent Densal® and solution heat treat processes. In fact an approximate ratio of casting volume being processed-to-HIP vessel volume doing the processing exists that determines whether or not the combined process is more energy efficient than the independent processes. If the volume of castings within the vessel is sufficiently small in comparison to the total HIP vessel volume, the energy required to overcome the cooling which results from the adiabatic gas expansion makes the combined process less energy efficient than the independent process.
- However, the desire to achieve maximum process efficiency dictates that most full runs are run at the HIP vessel capacity, so the likelihood of a partially loaded HIP vessel can be discounted. In the worse case scenario of loading the HIP vessel to maximize subsequent quench rates, the casting volume-to-vessel volume would still be sufficiently high to ensure energy savings. Therefore, allowing that the volume percent of castings in the HIP vessel will always be greater than the threshold value suggested herein, the combined process, even conservatively estimated could increase

energy efficiency of the densification/heat treat portion of the production of critical application aluminum castings by as much as fifty percent.

- These results warrant further investigation into the implementation of a commercial combined Densal®/solution heat treat process.