Research Programs

Fatigue Performance of Fluidized Bed Heat Treated Castings

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Introduction

A typical heat treatment regimen for a typical aluminum cast alloy is comprised of a solutionizing step, followed by quenching in water and an aging step. Together, these three steps may last for over ten hours and contribute a substantial increment to the part's manufacturing cost. Fluidized beds offer a more efficient means of energy transfer than conventional heat treatment methods that rely solely on convection, and thus they present an attractive alternative to traditional heat treatment. Fluidized beds achieve very rapid heat treatment for three main reasons:

- Each component enters individually into the fluidized bed medium rather than stacked among many in a basket. This allows each component to experience the maximum heat transfer rate and a precise thermal profile that is identical to that of the other parts.
- Fluidized bed heat transfer rate is superior to that of traditional hot air heat transfer.
- Fluidized beds hold a precise, even temperature throughout the heating medium, which ensures that all aspects of a component are quickly and uniformly heated, thus reducing component distortion and residual stress.

Objectives

This project is focused on to the study of fatigue behavior, residual stress, and part distortion of heat treated Al castings using fluidized beds. In addition, we aimed to engineer cast A356 alloy to reduce its quench sensitivity. The project had three primary objectives:

- Study the effect of fluidized bed (FB) heat treatment on fatigue performance of 319 alloy diesel heads.
- Explore the potential benefit of quenching using FB to minimize residual stress, and distortion of Al castings.
- Tailor composition of A356 alloy to decrease its quench sensitivity.

Project Overview

The aim of this project was to study the effect of FB quenching subsequent to solution heat treatment on properties such as fatigue life, residual stress/distortion. For comparison purposes, castings were quenched in water. The focus of the project was to improve the fatigue performance of Al castings through proper heat treatment using FB.Â Strategies followed during the project were:

- Carry out a critical literature review; Focus on fatigue performance of Al alloys
- Phase I: Fatigue analysis of FB heat treated 319 Al alloy diesel heads.
- Phase II: Residual stress and distortion analysis of Al castings heat treated using various quenchants, namely FB, water, and polymer based quenchants.

- Phase III: Reduce quench sensitivity of A356 alloy (Jominy Quench Test).

This project commenced in May 2005 and ended in April, 2007; the project was funded by the ACRC consortium members.
This project was divided into three phases:
Phase I - Effect of FB heat treatment on fatigue performance of Al castings

- Critical literature review on fatigue performance of Al alloys.
- Procurement of 319 alloy castings
- Heat treatment of 319 alloy using FB
- Fatigue testing
- Weibull analysis
- Mircrostructural and fractographic analysis
- Analysis and synthesis of results

Phase II - Effect of FB quenching on residual stress and distortion

- Residual stress tests on Al cast alloys (A356.2, and 319)
- Distortion measurements on Al cast alloys (A356.2)

Phase III - Effect of alloying elements such as Cu, Mg, Cr etc. on quench sensitivity of A356 alloy

- Casting of tailored A356 alloy Jominy bars
- Heat treatments: solutionizing (conventional furnace (CF)), Jominy quench test, aging (conventional furnace)
- Hardness measurement
- Quench factor analysis

Outcome / Impact

Phase I

- Fatigue strength of the 319 alloy treated to T6 temper is greater than those treated to T5 temper.
- At high stress level (above 90 MPa), samples treated to T6 condition shows the highest fatigue life as compared to T7 and T5.
- Duration of solution heat treatment (2 hours vs. 8 hours) has no significant effect on fatigue strength when the 319 alloy was aged at 250°C (i.e. T7). However, the fatigue strength of samples aged at 230°C (i.e. T6) is greater when the 319 alloy was solutionized for longer duration (i.e. 8 hours) as compared to shorter duration (2 hours).
- Weibull modulus (m) of T6 temper is greater than T7 and T5 temper. This implies that castings are more reliable when treated to T6 temper as compared to T7 and T5 tempers.
- The type of heat treatment (i.e. T5, T6 or T7) had no significant effect on characteristic fatigue life.
- Fracture surfaces of all samples tested at R=-1 showed three distinct regions: (I) crack initiation region at the surface or near to the surface, (II) crack propagation region (intermediate region), and (III) catastrophic/monotonic failure region. In most cases, multiple cracks were observed. In addition, only in few cases, cracks initiated either from inclusion/oxide particles or pre-existing pores present at or near to the surface. However, not all pre-existing pores proved to be detrimental. In some cases, cracks did not initiate from pre-existing defects such as oxides, pores etc.Â Defects such as pores and inclusions are detrimental only when they are present at or near to the surface.

- The monotonic failure region of T5 tempered 319 alloy exhibited greater faceted dimples. On contrary, in T6 and T7 tempered 319 alloy, dimples have reduced curvature. This indicates that 319 alloy treated to T5 temper undergoes lower degree of plasticity prior to fatigue failure as compared to those treated to T6 and T7 tempers.

Phase II

- The lower temperature gradients observed in the fluidized bed quenched plates resulted in significantly lower residual stresses as compared to the water quenched plates. The fluidized bed quenched plates exhibited stresses that were nearly 70% lower than stresses measured in the plates quenched in water at 21°C (70°F). Residual stresses measured in the fluidized bed quenched plates ranged from 10 to 20 MPa (1.5 to 2.9 ksi) regardless of orientation.

- Distortion was also decreased in the fluidized bed quenched plates. Plates oriented vertically exhibited minimal to no distortion. Plates oriented horizontally measured a distortion of 0.8 mm (0.031 in), which was still around a 40% reduction in distortion as compared to the water quenched plates.

Phase III

- Quench sensitivity of Al-Si-Mg cast alloys increases with increasing Mg content. The maximum quench factor (t) value of Al-Si-0.57Mg alloy is 145, which is significantly higher as compared to Al-Si-0.35Mg (t = 38) and Al-Si-0.45Mg (t = 35) alloys.
- Addition of 0.8wt% of Cu to A356 significantly lowers its quench sensitivity. The maximum quench factor value of Al-Si-0.45Mg-0.8Cu alloy is 16, which is the least value among all other alloys.
- The precipitation rate of Mg2Si particles in A356 alloy decreases with decreasing quench rate. On contrary, the precipitation rate of Al5Cu2Mg8Si6 in Al-Si-Mg-Cu alloy is relatively less dependent on quench rate.
- Simulation results showed that the addition of Cu in excess of 0.57 wt% to Al-Si-Mg alloy forms GP zones; These GP zones are heterogeneous sites for nucleation of precipitates and reduce the quench sensitivity of the alloy.

In addition, some fundamental studies on localized recrystallization in cast A356 alloy were carried out using dilatometer and calorimeter. A summary of key points are given below:

- Due to rapid heating in FB (Fluidized Bed), dislocations were generated at the Si/Al interface; whereas in CF (Conventional Furnace) with relatively slow heating rate, no dislocations were observed at the eutectic Si/Al interface.
- Recrystallization occured during the temperature ramp-up stage of solution heat treatment in cast A356 alloy. The evaluated value of activation energy of recrystallization in cast A356 alloy is 127 KJ/mol.
- Recrystallization in cast Al-Si alloys is a localized phenomenon and occurs in the vicinity of eutectic Si particles. This is in contrast to recrystallization in wrought alloys where recrystallized grains evolve throughout the matrix. The difference between recrystallization behavior in cast and wrought alloys is due to their differences in driving force for recrystallization. In the case of cast Al-Si alloy, the driving force for recrystallization is due to thermal mismatch between Al and Si, which is in-situ (i.e. generated during thermal cycle); whereas in the case of wrought Al alloys the

stored mechanical energy is the driving force for recrystallization, which is ex situ (i.e. generated during cold working prior to thermal treatment).

- Both dilatometry and DSC tests show that recrystallization temperature increases with increasing heating rate. This is in contrast to thermal analysis conducted by temperature measurements. This anomaly is however less clearly understood and further investigation is needed to explain the observed result.
- Creep occurred in A356 alloy when the sample was heated slowly at a rate of 4.3 oC/min. However, samples heated at higher heating rates (520, 130 and 17.3 oC/min) did not result in permanent deformation due to creep.

<u>Publications</u>

- S.K. Chaudhury, D. Apelian, J. Keist, and P. Meyer, On Fatigue Performance of Fluidized Bed Heat Treated 319 Alloy Diesel Cylinder Heads, accepted for publication in Metallurgical and Materials Transactions A, Publisher:Springer.
- S.K. Chaudhury, D. Apelian, J. Keist, and P. Meyer, Microstructure and Mechanical Properties of Heat treated 319 Alloy Diesel Cylinder Heads, Accepted for publication in Metallurgical and Materials Transactions A, Publisher:Springer.
- J. Keist, D. Dingmann, C. Bergman, Fluidized Bed Quenching: Reducing Residual Stresses and Distortion, in proceedings of the 23rd ASM Heat Treating Society Conference, September 25-28, 2005, Pittsburgh, Pennsylvania, USA, Edited by: D. Herring and R. Hill, p. 263-270.
- S.K. Chaudhury and D. Apelian, Effects of Mg and Cu Content on Quench Sensitivity of Al-Si-Mg Alloy, To be submitted for publication in Journal of Materials Science, SpringerLink publication.
- S.K. Chaudhury, V. Warke, S. Shankar, and D. Apelian, Localized Recrystallization in Cast Al-Si-Mg Alloy During Solution Heat Treatment: Dilatometric and Calorimetric Studies, Accepted for publication in Metallurgical and Materials Transactions A, Publisher:Springer.