Evaluation of Distortion and Residual Stresses During Heat Treatment of Aluminum Alloys
Report 07 #2 - A.4

Research Team:
Makhlouf M. Makhlouf, Professor (508) 831 5647 mmm@wpi.edu
Chang-Kai Wu (Lance), M.S. Student (508) 831 5631 lancewu@wpi.edu

Focus Group Members
Geoffrey Sigworth ALCOA Technical Center
Fred Major ALCAN International
Ray Donahue Mercury Marine
Paul Crepreau (Qigui Wang) General Motors Corp.

PROJECT STATEMENT

Objectives
The objective of this project is to develop and verify a computer simulation software and strategy that enables the prediction of the effects of heat treatment on cast aluminum alloy components. The simulation should accurately predict dimensional changes and distortion and residual stresses.

Strategy
The project is divided into three major tasks as follows:
Task 1 aims to develop the data necessary for the model.
Task 2 aims to model the heat treatment response of a cast aluminum alloy component.
Task 3 aims to verify the model predictions against measured data.
**PROJECT TASKS**

**Task 1: Generate Input Data for the Model**

*Determine the heat transfer coefficient:*

Probes are machined from cast A356 alloy in order to use them in measuring the heat transfer coefficient during quenching.

The probes are quenched in the CHTE quench system, and the heat transfer coefficient is calculated from the time temperature data.

- Cast A356 parts
- Machine probes
- Perform quenching experiments
- Calculate heat transfer coefficient

*Measure temperature-dependent mechanical properties:*

This work will be performed at University of Alabama.

- Establish contact at University of Alabama
  Perform measurements on Gleeble

**Task 2: Model the Response of a Cast Aluminum Alloy Component**

*Design and manufacture the test component*

- Design the part
- Manufacture the part

*Model the test component*

A case study simulation is performed using the DANTE/ABAQUS model and depicting the heat treatment behavior of the part.

Results from this case study are compared to measured distortion and residual stresses in the parts due to heat treatment.

- Preliminary modeling (learning curve)
  Model the cast part

**Task 3: Verify the Model Predictions**

Measurements will be performed on the cast parts in order to characterize the effect of heat treatment on:

- Measure distortion and dimensional changes
- Measure residual stresses

✓ = Performed work
ACHIEVEMENTS TO DATE
See Appendix A for a report on the status of the project.

CHANGES IN PROJECT STATEMENT
None

WORK PLANNED BEFORE THE NEXT ACRC MEETING
- Measure the elevated temperature mechanical properties of A356 alloy, including elastic modulus, yield stress and plastic strain, using a Gleeble machine.
- Measure distortion and dimensional changes on cast parts using a CMM.
- Begin x-ray measurements for assessing residual stresses in A356 cast parts.

PROJECT DELIVERABLES
The deliverable from the project is a tested software and strategy for predicting the effect of heat treatment on the characteristics of cast aluminum alloy components.
An equally important deliverable from the project is an assessment of the significance of metallurgical effects, e.g., solution and precipitation of alloying elements, on distortion and residual stresses in components that are cast from commercial Al-Si alloys.

PROJECT SCHEDULE
The expected completion date of the project is December 2009.
APPENDIX A

Status Report
Introduction

Aluminum alloy cast components experience considerable changes during heat treatment. These include changes in mechanical properties, in dimensions, in magnitude and sense of residual stresses, and in metallurgical phase composition. Since the quality assurances criteria that heat-treated cast components must meet include prescribed minimum mechanical properties and compliance with dimensional tolerances, it is necessary for casters to be able to accurately predict these changes in order to take appropriate measures to prevent their harmful effects and insure the production of good quality parts. Satisfactory response to heat treatment is often gauged by the ability of the component to be heat treated to a desired microstructure, hardness and strength level without undergoing cracking, distortion or excessive dimensional changes.

In addition to the completely reversible changes that are caused by thermal expansion and contraction, metallic components experience permanent dimensional changes during heat treatment. These permanent changes can be classified into three main groups based on their origin:

1. Dimensional changes with mechanical origins, these include dimensional changes caused by stresses developed by external forces, dimensional changes arising from thermally induced stresses, and dimensional changes caused by relaxation of residual stresses.

2. Dimensional changes due to quenching, these are dimensional changes that occur during quenching or that result from stresses induced by quenching.

3. Dimensional changes with metallurgical origins, these include dimensional changes caused by re-crystallization, solution and precipitation of alloying elements, and phase transformations.

Residual stresses often adversely affect the mechanical properties of cast components. They are caused by differing rates of cooling during quenching and depend on the differential rate of cooling, section thickness, and material strength. Reducing the severity of the quench results in lower residual stresses, but with a corresponding reduction in material strength.

This project will focus on predicting (1) residual stresses, (2) dimensional changes that have mechanical origins and (3) dimensional changes that are caused by quenching. Dimensional changes with metallurgical origins will be included in a follow up project – subject to recommendation by the project’s Focus Group and approval of the ACRC Steering Committee.

Research Plan

The model is based on a modification of the commercially available finite element analysis software ABAQUS\(^1\). This software can perform all the required simulations provided that the necessary material’s properties are made available to it. These include thermal properties, such as the coefficient of thermal expansion, the specific heat, etc., and mechanical properties, such as the modulus of elasticity, the yield strength, etc., all as functions of temperature. Consequently, the first Task in the project will focus on generating the necessary database. Once, this is accomplished, the second Task in the project will commence and will focus on using the software to predict the heat treatment response of a particular component cast from an aluminum alloy. In the third Task, the predicted responses will be compared to experimentally measured responses and a modeling/prediction strategy will be formulated and recommendations will be made to the consortium members.

---

\(^1\)ABAQUES is marketed by Slovia, Inc. Rhode Island, USA.
Status Report

Aluminum casting alloy A356 will be used to develop and demonstrate the procedure for obtaining the necessary database and modeling the response of aluminum alloy cast components to heat treatment. The methodology developed for A356 alloy can be extrapolated to other Al-Si alloys.

The project is divided into three main Tasks as follows:

**TASK 1: Generation of Input Data for the Model**

An extensive material database is being generated for use as input to the ABAQUES model. This data includes mechanical and physical properties, and heat transfer coefficients for various process steps as functions of temperature.

The development of this data and its incorporation into the Software is the major focus of Task 1. Subtasks 1.1, 1.2, and 1.3 provide details of the work.

**Subtask 1.1: Measurement of the heat transfer coefficient**

This data is primarily used by the thermal module in ABAQUES to compute the heat that transfer into and out of the part during heat treatment. Different heat environments are included, such as furnace, water and air.

Even the most sophisticated software uses fundamental laws of heat flow to numerically model the heat transfer process. As a result, the accuracy of the model predictions invariably depends on the accuracy of the boundary conditions, initial conditions and material property data used in the heat flow equations. While the material property data is relatively easy to determine and the initial conditions are usually known, the boundary conditions between the metal part and the quenching medium, i.e., the heat transfer coefficient, are dependant on many factors including the initial conditions, the geometry of the part, the chemistry of the part and the quenching medium, and the surface condition of the part. Moreover, some of these factors may interact with one another. Because of the critical nature of the heat transfer coefficient in computer modeling, an effort is made to provide a system and procedure for accurately determining this parameter.

The material used in this project is commercial aluminum A356 Alloy with the chemical composition shown in Table I.

| Table I. Composition of the A356 alloy in wt.% |
|-----------------|--------|--------|--------|--------|--------|----------------|
| Si              | Fe     | Cu     | Ti     | Mg     | Zn, Mn, .. |
| 7.25            | 0.08   | 0.005  | 0.27   | 0.27   | < 0.002  |

The measurement of heat transfer coefficient involves quenching a heated cylindrical probe machined from a cast piece of A356 alloy and equipped with a thermocouple connected to a fast data acquisition system into the quenching medium and acquiring the temperature-time profile. The probe dimensions are chosen such that the Biot number for the quenching process is <0.1. This insures that significant thermal gradients will not be present in the radial direction in the probe. Accordingly, a simple heat balance analysis (usually referred to as a lumped parameter
analysis) can be performed on the system (probe + quenching medium) to yield the heat transfer coefficient. Since the Bi < 0.1, the error associated with the calculation of the heat transfer coefficient is less than 5%.

For this project, a small cylindrical probe (9.5 mm in diameter and 38 mm long) shown schematically in Figure 2, was cast from standard A356.2 alloy. A hole was drilled down to the geometrical center of this probe and a thermocouple was inserted for measuring the time-temperature data. Graphite powder was packed into the hole before the thermocouple was inserted in order to ensure intimate contact between the probe and the thermocouple. The probe was heated to the solutionizing temperature and held at that temperature for 20 min to ensure homogenization. Subsequently, the probe was quenched into water that was maintained at room temperature. While quenching, the temperature of the probe was acquired as a function of time using a very fast data acquisition system at a scan rate of 1000 scans/sec.

![Figure 1. Quench probe system.](image1)

![Figure 2. Quench probe-coupling-connecting rod assembly.](image2)
A heat balance applied to the probe results in Equation 1, which was used to calculate the heat transfer coefficient at the surface of the probe.

$$h = -\frac{\rho V C_p}{A_s \left(T_s - T_f\right)} \frac{dT}{dt}$$

(1)

In Eq (1), $h$ is the heat transfer coefficient at the surface of the probe, $\rho$, $V$, $C_p$, and $A_s$ are the density, volume, specific heat, and surface area of the probe, respectively. $T_s$ is the temperature at the surface of the probe, which, due to the geometry of the probe, is approximately equal to the measured temperature at the center of the probe. $T_f$ is the bulk temperature of the quenching medium. The derivative of temperature with respect to time in Eq (1) is calculated from the measured temperature vs. time data.

The heat transfer coefficient was calculated for quenching in room temperature. A quench tank with two liters of water was used and the probe was immersed completely. The temperature of the water before and after quenching remained constant at 17°C. The heat transfer coefficient that was calculated from this measurement will be used in the quenching step of the thermal model. The cooling curve obtained and the heat transfer coefficient calculated from Eq. (1) are shown in Figures 3 and 4, respectively.

![Figure 3](image1.png)

**Figure 3.** Measured cooling curve for A 356 alloy.

![Figure 4](image2.png)

**Figure 4.** Heat transfer coefficient for A 356 alloy.
Subtask 1.2: Measurement of the temperature-dependant mechanical properties of A356 alloy

This data is primarily used by the mechanics module in ABAQUES to compute the stresses that develop in the part undergoing heat treatment. These stresses are of two types, stresses due to a change in phase fraction and stresses due to plastic flow arising from thermal shocks.

In this project, it is assumed that the stresses developed because of precipitation of phases from the homogenized alloy is negligibly small, and so we will focus only on the stresses caused by plastic flow arising from thermal shock. Stresses caused by changes in phase composition will be included in a follow up project – subject to recommendation by the project’s Focus Group and approval of the ACRC Steering Committee.

A Gleeble machine will be used for measuring the mechanical properties of A356 alloy at elevated temperature. The elastic modulus, yield stress, and plastic strain will be calculated from the measurements.

An arrangement has been made to use the Gleeble machine at the University of Alabama. Work will commence on this Subtask in early January 2008. Five specimens will be used to measure mechanical properties at each of 7 temperatures: 25, 110, 195, 280, 365, 450, and 538°C. The measurements will be made at 3 different strain rates: 0.01, 0.1, and 1.0 s⁻¹. The total number of measurements is 7 (temperatures) × 3 (strain rates) × 5 (specimens) = 105.

Subtask 1.3: Measurement of the temperature-dependent physical properties

This data is primarily used by the thermal and stress modules in ABAQUES to compute the stresses that develop in the part undergoing heat treatment. Much of the thermal data for A356 alloy may be calculated using JMat Pro Software.

Task 2: Modeling the Response of a Cast Aluminum Alloy Component

A block diagram of the combined ABAQUES models is shown in Figure 5. It consists of a geometry and mesh generators, a post processor, the thermal module, and the stress module. The thermal module is setup to solve a heat transfer problem for each one of the steps of the heat-treating process, i.e., the furnace heating step, the immersion into the quench tank step, and the quenching step. The output file generated by the thermal module contains mainly the thermal history of the part during the various process steps. The stress module accesses this output file and calculates the residual stresses, the displacements, the volume fraction of metallurgical phases, and the hardness for the entire temperature history of the part.

Task 2 includes two Subtasks as follows.

Subtask 2.1: Design and manufacture of the test component

The part shown in Figure 6 is cast from A356 alloy to demonstrate and verify the model’s ability to predict the response of aluminum alloy cast components to heat treatment. The part was chosen in conjunction with the project’s Focus Group during the May 2007 meeting, and its geometry should extenuate the detrimental effects of heat treatment.
Figure 5. Solution procedure for the DANTE/ABAQUS combined model.

Figure 6. Cast component.
Subtask 2.2: Modeling the test component

A case study simulation was performed on the component manufactured in Subtask 2.1 using the ABAQUS model. Because the necessary data set for A356 alloy has not yet been completed (the temperature-dependant mechanical properties will be measured in January 2008), in this case study data gathered from various sources were used. The purpose of the case study is (1) become familiar with the software, and (2) demonstrate the ability of the software to perform the required task of modeling the heat treatment response.

The case study is based on a T6 treatment. Two different simulations of quenching the part were performed. In the first simulation, the part was quenched vertically into the water tank. In the second simulation, it was quenched horizontally into the water tank. See Figure 7.

The Thermal Module – The thermal module simulates the immersion step. The speed at which the part is immersed in the water tank was 10 m/s.

Vertical Immersion – In this simulation, it took the part 0.56 s to be completely immersed in water, and this caused a 6°C temperature difference between the bottom surface (the surface that contacted the water first) and the top surface (the surface that contacted the water last). The resulting temperature distribution is shown in Figure 8.

Figure 7. Schematic representation of the directions in which the parts were quenched.

Figure 8. Model predicted temperature distribution for vertical quenching.
**Horizontal Immersion** – In this simulation, it took the part 0.063 s to be completely immersed in water, and this caused a 4°C temperature difference between the left side (the side that contacted the water first) and right side (the side that contacted the water last). The resulting temperature distribution is shown in Figure 9.

![Temperature Distribution](image1)

**Figure 9.** Model predicted temperature distribution for horizontal quenching.

**The Mechanics Module** – This module uses mainly the time-temperature history of the part generated by the thermal module in order to calculate nodal displacements and stresses. For initial condition, the stress at all nodes was set to zero. If a known initial stress state existed, appropriate values could have been easily used.

The distortion in part geometry caused by quenching is shown in Figure 10. For better visualization, Figure 11 tracks the movement of one node (node No. 11629). In Figure 11, the part was immersed in the water quench tank after approximately 2000 step time, and the temperature drop is reflected in distortion of the part from this time onwards. Figure 11b is a “zoom in” of the time after 2,500 step time.

![Part Distortion](image2)

**Figure 10.** Distortion of the part caused by vertical quenching.
Figure 11. Distortion of vertically and horizontally quenched A356 cast parts.

Figure 12 shows the predicted residual stresses in the two principal directions, $\sigma_{11}$ and $\sigma_{33}$, due to vertical and horizontal quenching of the part.

Figure 12. Principal stresses generated from horizontal and vertical quenching of A356 cast parts.

Task 3: Verification of the Model Predictions

In this Task, the model predictions are verified by comparing them to measurements of corresponding parameters for parts made using processing conditions similar to those used in the simulation.

Task 3 is divided into two Subtasks as follows.

Subtask 3.1: Measurement of dimensional changes and distortion

A Starrett coordinate measuring machine (CMM) will be used to measure the dimensional changes and distortion caused by the heat treatment process. Sufficient measurements will be made in order to obtain accurate representation of the part before and after heat treatment.
**Subtask 3.2: Measurement of residual stresses**

The standard x-ray diffraction method for measuring residual stresses in metallic components will be used. In this method, line shifts due to a uniform strain in the component are measured and then the stresses in the component are determined either by a calculation involving the elastic constants of the material or by a calibration procedure involving measurement of the strains produced by known stresses.

If the inter-planar spacing between the diffracting crystallographic planes of the material in the un-stressed state \( d_0 \), together with the modulus of elasticity in the diffracting crystallographic direction, \( E \) and Poisson’s ratio in that same crystallographic direction, \( \nu \), are known then the two components of the biaxial principal stresses \( \sigma_1 \) and \( \sigma_2 \) can be calculated from Eq. (2).

\[
\frac{d - d_0}{d_0} = \left( \frac{1 + \nu}{E} \right) \sigma_\phi \sin 2\psi - \frac{\nu}{E} (\sigma_1 + \sigma_2)
\]  

(2)

The inter-planar spacing between the diffracting crystallographic planes of the material in the un-stressed state \( d_0 \) can be determined from Bragg’s law, Eq (3),

\[
n\lambda = 2d_0 \sin(\theta)
\]  

(3)

In Eq. (3), \( \lambda \) is the wave length of the x-rays used, and \( \theta \) is the diffraction angle.

It is important to emphasize that \( E \) and \( \nu \) in Eq. (2) are for the diffracting plane. Using the bulk values for \( E \) and \( \nu \) can induce a significant error in the magnitude of the measured residual stress. For example, in aluminum-based alloys, the x-ray line commonly used for calculating residual stress is (311); and for 7075 alloy, \( E/(1+\nu) \) for (311) planes is \( 8.83 \times 10^6 \) psi while \( E/(1+\nu) \) for the bulk material is \( 7.82 \times 10^6 \) psi (\( \Delta \% = 12.9 \)).

**Method for determining \( E/(1+\nu) \) for the (311) planes in A356 alloy** – A tensile bar cast from A356 alloy is placed in the x-ray diffractometer and the two components of the biaxial principal surface stresses \( \sigma_1 \) and \( \sigma_2 \) are calculated using Eq. (2), wherein the values of \( E \) and \( \nu \) are the bulk values. \( \sigma_1 \) and \( \sigma_2 \) are then used to calculate the mean stress, \( \sigma_\phi \).

A sensitive strain gage is then applied to the surface of the tensile test bar as shown in Figure 13, and the tensile test bar is pulled in a testing machine. The surface strain that is measured by the strain gage is converted to a surface stress using Hooke’s Law,

\[
\sigma_\phi = E\varepsilon
\]  

(4)

The mean surface stress obtained from Eqs. (2) and (4) must be equal; i.e. a plot of \( \sigma_\phi \) calculated from Eq. (2) vs. \( \sigma_\phi \) calculated from Eq. (4) should yield a straight line with slope = 1.0 as shown in Figure 14. However, the slope of the straight line obtained will deviate from 1.0 because of the use of the bulk values of \( E \) and \( \nu \) in Eq. (2) rather than \( E \) and \( \nu \) values for (311) planes. The correction multiplier that is needed to bring the slope to 1.0 is multiplied by \( E/(1+\nu) \) for the bulk material in order to obtain \( E/(1+\nu) \) for the (311) planes. This is then used in Eq. (2) to obtain the correct residual stress.
Figure 13. Strain gage affixed to tensile test bar.

Figure 15. Plot of $\sigma_\phi$ calculated from Eq. (2) vs. $\sigma_\psi$ calculated from Eq. (4).