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COMPUTER MODELING OF AGE HARDENING PROCESSES FOR 7075 ALUMINUM COMPONENTS

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Abstract

A project was recently completed to characterize the solution treatment and age hardening kinetics of 7075 aluminum and to build software to predict the dimensional change, stress state and metallurgical state of components subjected to an age hardening process. The state of the microstructure was characterized using electrical resistivity, hardness and tensile properties. Phase transformation kinetics parameters for simplified dissolution and aging models were developed from the experimental data. The transformation models were implemented into an internal state variable material model linked to a commercial finite element solver. A production "T" shaped forging was dimensionally characterized before and after heat treatment, and served as the software validation component. Comparison of actual and predicted dimensions showed merit to both the modeling method and the experimental procedures used to gather the necessary property data.

Introduction

Controlling part distortion and residual stress during heat treatment is important to manufacturing economics and to part performance. For aluminum alloys such as 7075 that are solution treated and age hardened, thermal stress during the quenching step and dimensional change during aging contribute to both distortion and residual stress. At present, it is difficult for designers to quantitatively account for the dimensional changes and stresses experienced during these heat treating steps. A project was undertaken to develop a finite element based capability for predicting the microstructural changes, the accompanying dimensional changes and internal stress state changes that occur during heat treatment of 7075 aluminum parts. Data to characterize the mechanical, thermal and metallurgical behavior of 7075 aluminum were measured and collected.[1] Then, parameters were determined from these data to drive a constitutive model for finite element modeling of aluminum alloy heat treatment. A "Tee" shaped forging was selected to demonstrate the feasibility of such process simulation, and results are reported.

Heat Treatment Simulation

The BCJ internal state variable (ISV) material model used in the commercial software DANTE® for simulating heat treatment of steel parts was modified to accommodate the metallurgical transformations and diffusion kinetics of the aluminum alloy. Toward this end, a decision was made to treat the aluminum microstructure at a macroscopic level as being composed of three possible "phases", namely solution treated, age hardened, and over-aged.

Heat treatments would then alter the phase volume fractions, depending on the particular time and temperature combination being applied. The thermal and mechanical properties would be dependent of the volume fractions of the three phases in accordance to a rule of mixtures.

The rationale for selecting this macroscopic approach to simulation of aluminum alloy heat treatment was to avoid directly modeling the complex details of microscopic precipitation and growth of second phases at this point in model development. With proper hooks or use of equation parameters, these details can be added as further work is performed.

Mechanical constants for the ISV model for each of the "phases" were determined from the tensile data, augmented with data from the published literature. Thermal properties were based on published literature data. The important data for thermal expansion behavior and strain associated with transformation from one phase to another were based on CWRU measurements.

Mathematical Description of Age Hardening Kinetics

A rate based mathematical approach was taken for describing the kinetics of age hardening, over aging and dissolution of second phases. The overall transformations during cooling of solution treated material were limited to:

ST → ST	upon rapid quenching
ST → A	upon slow cooling
ST → A → OA	upon slower cooling

where ST indicates solution treated microstructure, A indicates aged microstructure, and OA indicates over-aged microstructure.

During heating, the transformations to be modeled were:

ST → A	during age hardening
A → OA	during prolonged age hardening and heating to solutionize
OA → ST	during solution treatment

The competition among these transformations is dependent on the heating or cooling rates, temperatures and time at temperature.

A modified Avrami modeling approach was used to describe the diffusion controlled phase transformations that occur during age hardening for this alloy. The general equation form for these transformation rates for cooling and heating was:

$$V = 1 - \exp[-t^n/k] \qquad \text{eq.(1)}$$

where V is volume fraction of the product phase,
t is time at temperature in seconds,
n is a material dependent exponent, and
k is a temperature, time and material dependent parameter.

The terms used to calculate n and k are determined by curve fitting experiment data for isothermal aging tests that plot volume fraction of aged material on temperature vs. time chart. These data form the classical "C" curves associated with diffusion controlled transformations. Terms were fit from the CWRU data and the volume fraction vs. time curves calculated for four aging temperatures is shown in Figure 1.

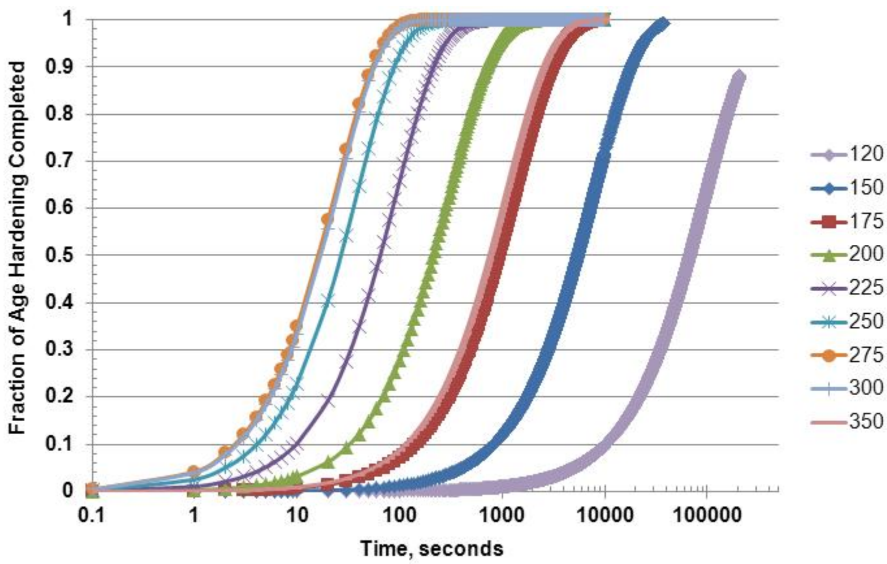

Figure 1. Volume fraction of “Aged” 7075 Al as a function of time for indicated aging temperatures.

<u>Data Checking</u>

Once the kinetics model parameters, the ISV model parameters, and several other characteristic properties such as densities, thermal conductivities, specific heats have been defined, the accumulated parameters and values were tested. In this case, two dimensional, axisymmetric models of the experiments, such as prediction of length change due to solution treatment, age hardening, and over aging, were executed and predictions were compared against measured results. The model described below was used to check kinetics model parameters for accuracy.

A thin disk of 25.4 mm (I inch) in diameter was meshed and subjected to defined heat treatment schedules. The model allowed heat to flow in and out of the outer diameter only, so it acted as an infinitely long bar. The initial microstructure was assumed to be an over-aged microstructure. The objective of the model was to exercise the kinetics models. Process variables examined included:

- time needed for solution treatment
- quench rate required to maintain the solution treated microstructure
- age hardening response

Figure 2 shows the phase fractions and temperature over the solution treat and age heat treat schedule. The transformations behaved as anticipated from the model data. Figure 3 shows a closer view of the solutionizing step, with the over aged microstructure decreasing with holding time. Once the disk temperature was above about 440°C (824°F), solutionizing started and after nearly 1 hour at 480°C (900°F), the structure was predicted to be fully solutionized. Figure 4 shows a closer view of the age hardening step. Once at the age hardening temperature of 140°C (285°F), approximately 3.6 hours was needed to complete age hardening. Overall, the kinetics parameters used in the disk model were judged to be reasonable.

Several important trends were learned from the disk model. First, the high thermal conductivity of the aluminum minimized thermal gradients within the disk. Also, the high thermal diffusivity avoided precipitation during quenching, so thermal stress was the main issue for distortion control, not phase change.

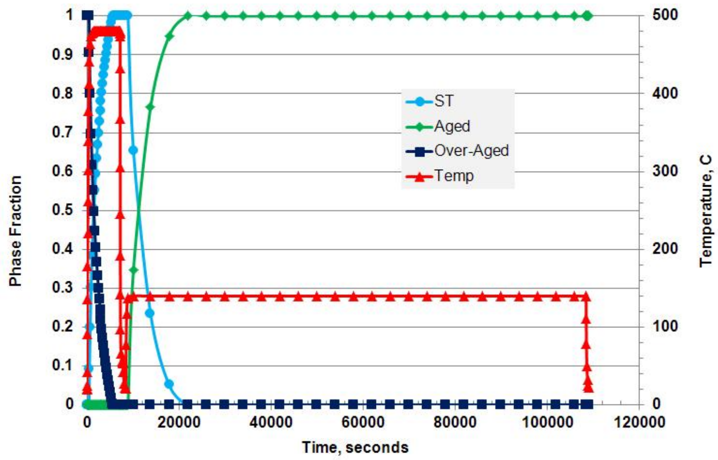

Figure 2. Predicted phase fractions and temperature for the 25.4 mm diameter disk model.

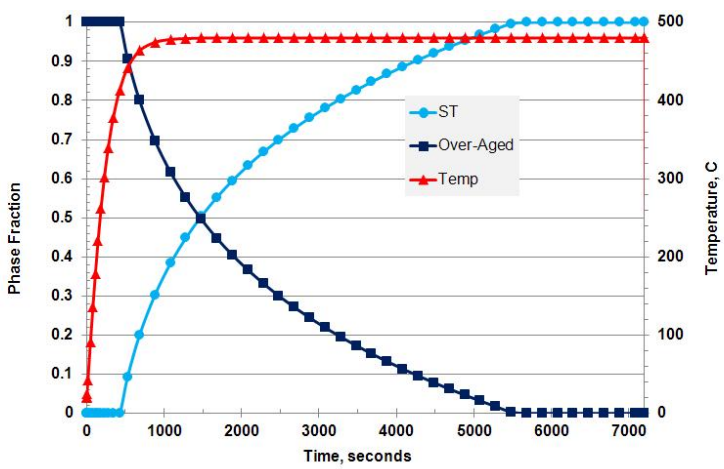

Figure 3. Predicted transformation of the over-aged structure to the solution treated structure during heating of the disk model.

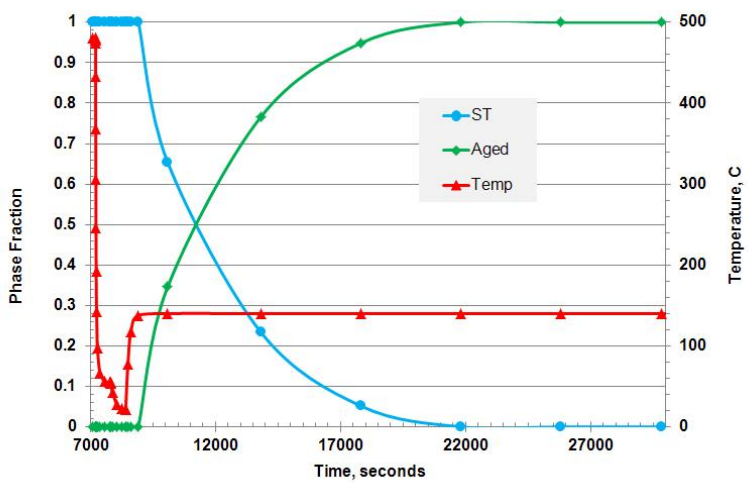

Figure 4. Predicted age hardening response for the disk model for aging at 140°C (284°F).

Simulation of “Tee” Forging

A demonstration component for the project chosen after discussion with a local forging company was a “Tee” shaped part forged from 7075 aluminum bar stock. This is a hot forging where multiple parts are forged as a platter from one bar stock mult. The parts are cold trimmed from the platter, and then heat treated. The forging company supplied parts to CWRU that were in the as-forged condition and the age hardened condition. Measurements of the before and after age hardening were made using a coordinate measurement machine. Using these measurements, dimensional change due to heat treatment was determined, and this change was used as a comparison point for computer simulation for the heat treatment process.

A photograph of the trimmed forging is shown in Figure 5. The overall length of the forging is approximately 10.5 cm (4.14 inches) and the diameters of the cylindrical sections are about 3.6 cm (1.4 inches) for a frame of reference. It was not possible to build a solid model of the exact forged shape because of trim lines other forging features not present in the CAD model, but the solid model constructed was sufficiently close to the forged shape to allow comparisons.

Taking advantage of symmetry, a quarter symmetry finite element mesh was developed and is shown in Figures 6. To capture temperature gradients that develop during heating and cooling steps, especially during rapid heating and cooling, fine mesh spacing was used near all surfaces. Thermal processing of the “Tee” forging followed the schedule presented in Table I. An assumption was made that heating and cooling conditions were uniform over all the part surfaces, and this allowed symmetry to be assumed. The quarter symmetry model had 86,741 nodes and 80,508 hexahedral elements.

Figure 5. “Tee” forging of 7075 aluminum.

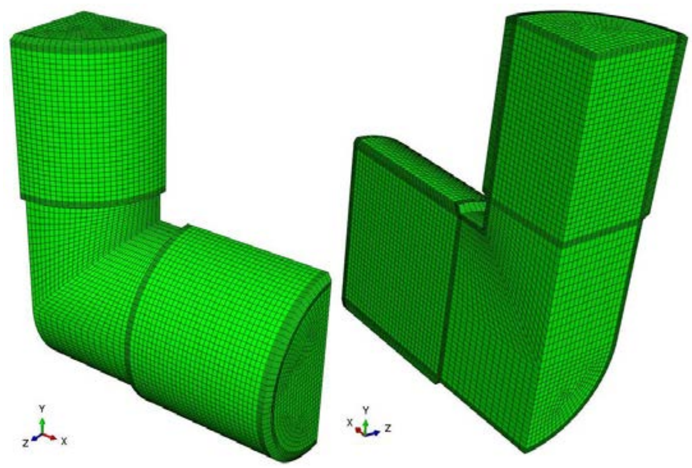

Figure 6. 3D mesh used for quarter symmetry model of “Tee” forging.

Table I. Heat Treat Schedule for “Tee” Part Model

Step	Temperature	Time
Solution Anneal	475°C (887°F)	2 hours
Transfer	100°C (212°F)	10 seconds
Quench	40°C (104°F)	10 minutes
Cool to Ambient	20°C (68°F)	10 minutes
Age Harden	140°C (284°F)	8.3 hours
Cool to Ambient	20 (68°F)	10 minutes

Model Results

Model results are shown in Figures 7 through 12. Figure 7 shows a graph of phase fractions and temperature vs. model time at the model center, and Figure 8 shows stress and temperature vs. time for this same location. During the heating period, the over-aged structure transformed to the solution treated structure. Stress generated during this period was low and the thermal gradient was relatively small during the early stage of heating. The solution treated condition was maintained during water quenching. Early in the quenching step, the temperature gradient was maximum and the highest surface stresses were experienced as the surface cooled and tried to contract around the hotter core of the part. The solution treated phase did transform to the age hardened phase during aging, as expected. Stresses remained low during this step.

It is during quenching that more critical events occur. The temperature distribution after 0.7589 seconds of quenching is shown in Figure 9. The overall temperature gradient is over 100 C, and at this time there is also a gradient over the external surface, with corners cooling fastest. As a consequence, Figure 10 shows that inner corners experience higher stress than other features, and there is a general outside to inside stress difference since the external surfaces are trying to shrink while the internal regions are lagging behind.

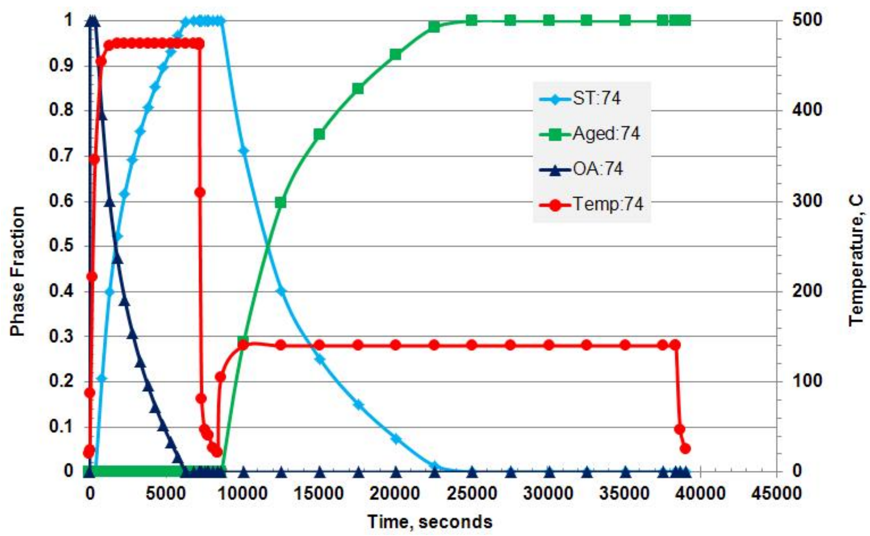

Figure 7. Predicted phase fraction and temperature evolution at "Tee" model center.

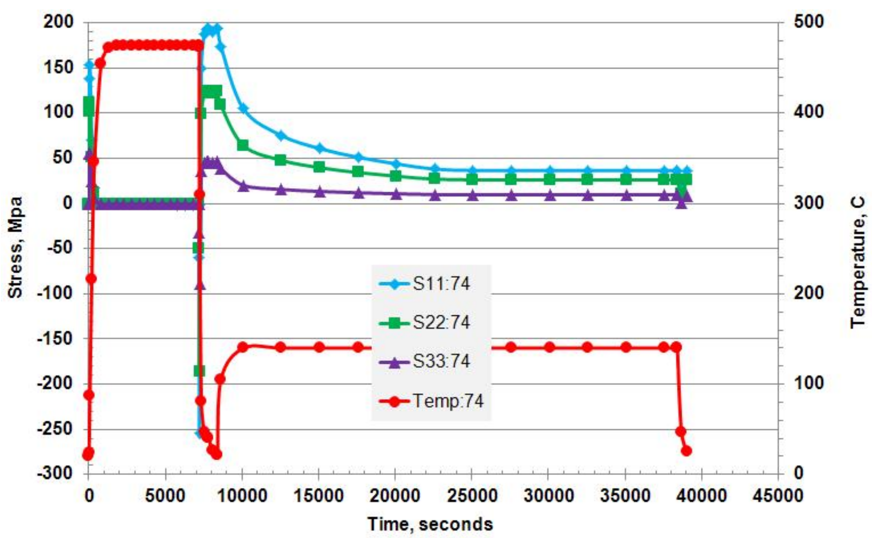

Figure 8. Predicted stress and temperature evolution at "Tee" model center.

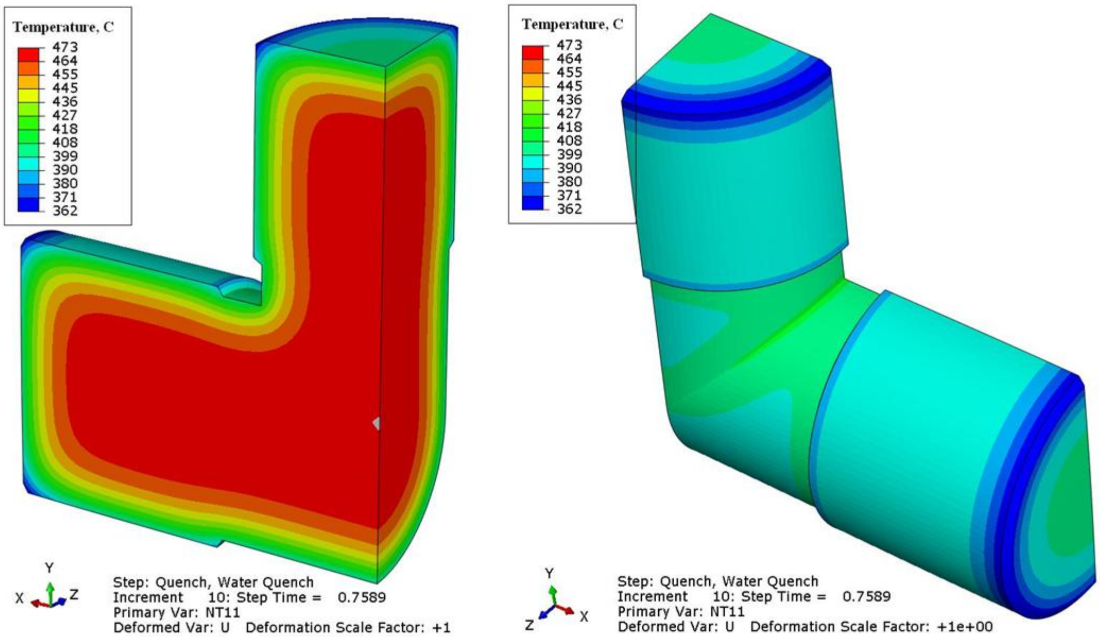

Figure 9. Predicted temperature distribution after 0.7589 seconds of quenching. The internal temperature distribution is shown on the left and the external profile is on the right.

Figure 11 shows the phase fractions for the solution treated and age hardened phases after 2119 seconds of heating at 140°C (284°F). As the figures show, age hardening is occurring fairly uniformly throughout the part interior, and at this time, almost 65% of the solution treated structure remains to be transformed.

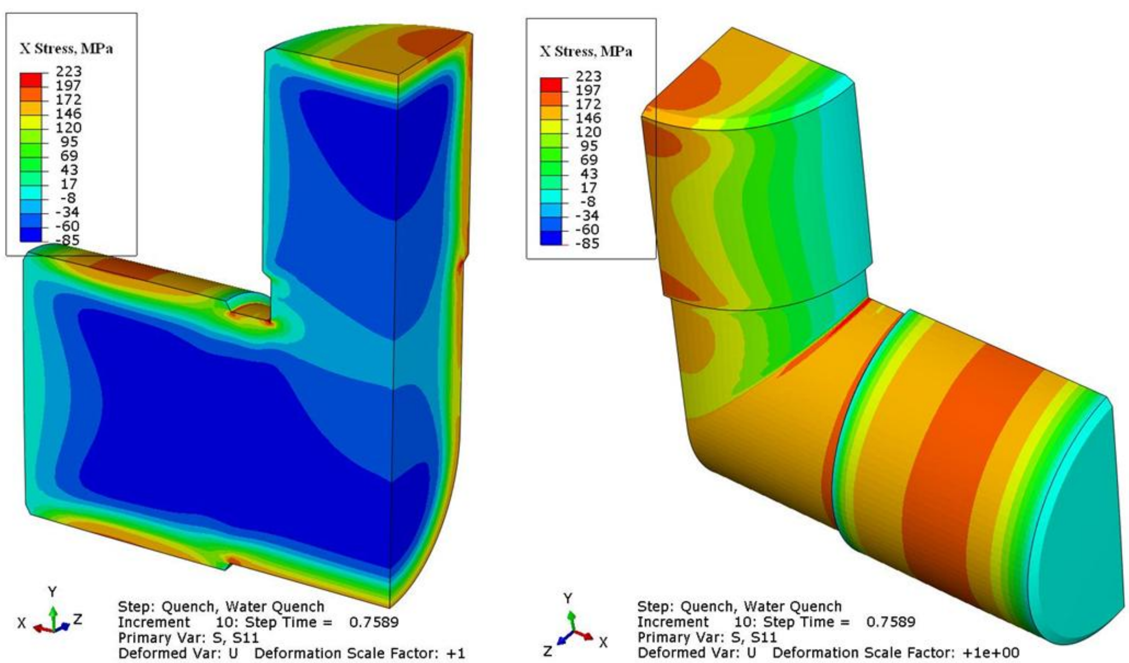

Figure 10. Predicted stress in X direction (horizontal) after 0.7589 seconds of quenching.

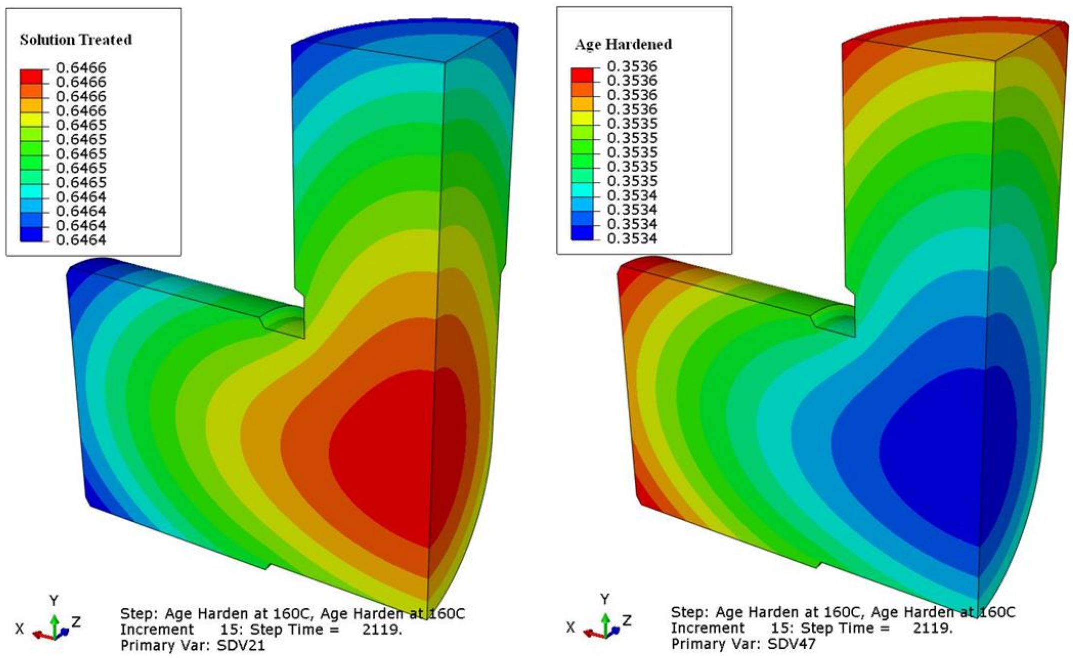

Figure 11. Predicted phase fractions for solution treated (left) and age hardened (right) structures after 2119 seconds of aging at 140°C (284°F).

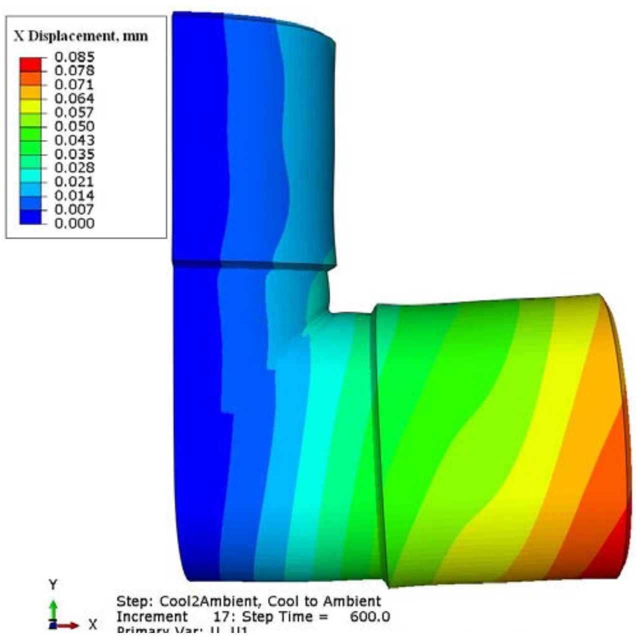

Figure 12. Predicted final dimensional change in the X direction.

Starting from the pure circular data which had a radius of 18.415 mm, the predicted change in radial growth due to heat treatment around the 90 degree arc is not uniform, with the radial strain being over 0.001. Figure 13 reports dimensional change in the x or horizontal direction due to heat treament. The figure shows that final growth is predicted for this direction, with the end face growing 64 microns to 85 microns. The figure shows bending of the “Tee” section, as indicated by the non-uniform end face growth.

During age hardening, the X direction dimensional change of the center of the YZ end face of the cylindrical section of the mesh during age hardening at 160 C was predicted to shrink during age hardening, with a strain value of -0.00041. This is in good agreement with the length strains reported in reference 1 for the thin rod sample length measurements during aging.

Summary

A finite element based methodology was developed and the feasibility of modeling heat treatment of an age hardening aluminum all was demonstrated for predicting the stress state and dimensional changes of a 3 dimensional part, in this case a "Tee" forging made of 7075 aluminum. Mechanical and metallurgical kinetics data were used to determine parameters needed to drive an internal state variable model based on the Bammann-Chiesa-Johnson model used in the DANTE software for heat treat simulation.

Acknowledgement

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Reference

1. D. Schwam, et al., "Data Development for Modeling Heat treatment of 7075 Aluminum Alloy Components," to be published in Proceedings of Advanced Materials, Processes and valuation Methods for Aerospace and Defence Applications, COM 2013, hosted by MS&T 2013, October 27-31, 2013, Montreal, Quebec, Canada.