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# DATA DEVELOPMENT FOR MODELING HEAT TREATMENT OF 7075 ALUMINUM ALLOY COMPONENTS

David Schwam[1], James McGuffin-Cawley[1], B. Lynn Ferguson[2], Andrew M. Freborg[2]

[1] Dept. of Materials Science & Engineering, Case Western Reserve University, Cleveland, OH

[2] Deformation Control Technology, Inc., Cleveland, OH

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## Abstract

Computer modeling of age hardening alloys such as 7075 aluminum requires characterization of the solutionizing and ageing kinetics of the alloy. In addition, the thermal and mechanical behavior of the microstructure in various states must also be characterized. Tools used to characterize solution treatment and age hardening included measurement of dimensional change, electrical resistivity measurements, hardness and tensile tests, and metallography. This presentation reports results of an experimental program for these characterizations. Electrical resistivity was measured at room temperature for solution treated, over aged and mill processed (T651) conditions, and also at room temperature after ageing over a range of times and temperatures. Tensile tests were conducted at both room temperature and the aging temperature. Hardness was measured at room temperature for the many microstructural conditions. These data collectively were then used to determine parameters to drive computer models of the heat treat process.

## Introduction

In a push to improve fuel economy, the US Department of Energy has funded a light weight vehicle initiative for several years. Because of its low density and relatively high strength capability, the use of aluminum alloys has been one of the focal points of the supported projects. Standard processing of parts includes a solution treatment step and an age hardening step for forged or worked components. The thermal stresses experienced during solution treating, which includes both heating and quenching, can cause part distortion. Age hardening can further distort the part due to thermal stress (less likely) and transformation induced stress (more likely). Modeling of these process steps provides a means for predicting such distortion so that it can be accounted for in the design process instead of trying to correct for it after it has occurred. However, accurate data for the alloy in question and the process are required. This paper presents work done to develop data for 7075 aluminum that are needed to model the solution treatment and age hardening process steps.

## Experimental

Alloy 7075 extruded bar stock with a diameter of 22.2 mm was procured for testing. The bar stock chemistry is given in Table I, and the as-received microstructure (T651 condition) is shown in Figure 1. The tensile properties for this material as supplied by the material supplier are listed in Table II.

Table I. Chemical Composition of Al 7075 Bar Stock

| | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Others | | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | each | total | |
| Max., w/o | 0.09 | 0.17 | 1.7 | 0.04 | 2.6 | 0.21 | 5.9 | 0.03 | <0.05 | <0.15 | balance |
| Min., w/o | 0.05 | 0.12 | 1.5 | 0.01 | 2.3 | 0.19 | 5.5 | 0.02 | | | |

Table II. Tensile Properties of the Al 7075 Bar Stock in T651 Condition

| sample | Ultimate Tensile Strength | 0.2% Offset Yield Strength | Total Elongation |
|---|---|---|---|
| #1 | 581.7 MPa (84.3 ksi) | 534.1 MPa (77.4 ksi) | 15.5% |
| #2 | 576.8 MPa (83.6 ksi) | 528.5 MPa (76.6 ksi) | 15.5% |
| #3 | 587.2 MPa (85.1 ksi) | 532.0 MPa (77.1 ksi) | 14.0% |
| #4 | 572.0 MPa (82.9 ksi) | 516.8 MPa (74.9 ksi) | 13.5% |

Sample Geometries

Rod shaped and disc shaped samples were machined from the bar stock for physical property measurements. Dimensions of the rods were 63.5 mm long by 6.35 mm in diameter. Two disc sizes were prepared: 5.84 mm in diameter by 1.52 mm thick, and 12.7 mm in diameter by 2.54 mm thick. Slightly thicker cylinders were machined for microstructural evaluation. Standard tensile bars with a gage diameter of 12.83 mm and overall length of 127 mm were machined.

Experimental Set-Up for Heat Treatments

To examine the effects of time at temperature on microstructure and hardness, samples were heated in a box furnace at 315°C for 4 hours to produce an over-aged microstructure. This was the starting microstructure for all subsequent heat treating trials. Figure 2 shows the typical microstructure for this over-aged material. The formerly unresolvable precipitations have grown to resolvable particles within the grains. Grain boundary films have also formed.

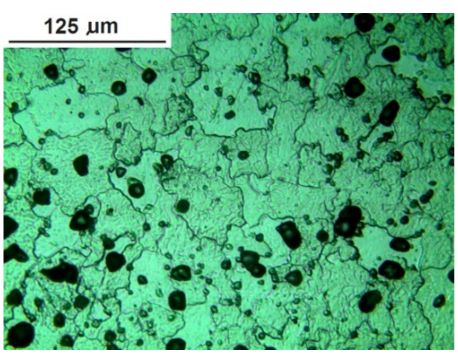



Figure 1. As received microstructure of 7075 Al alloy in T76 condition.

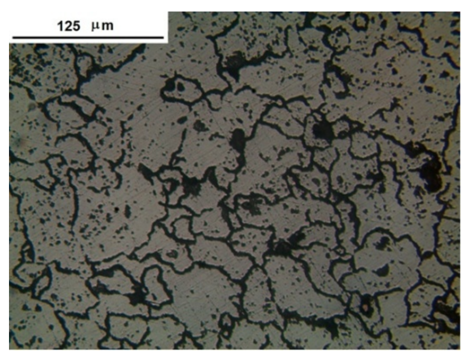


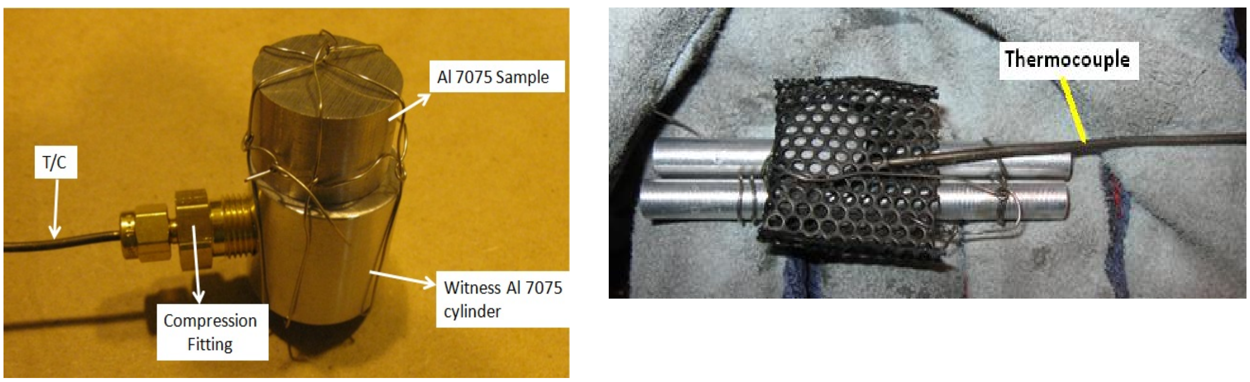

Figure 2. Over-aged microstructure produced by holding sample at 315 C for 4 hours.

Salt Pot Heating

A salt pot was configured for heating samples quickly and for controlled time periods. The salt was contained in a stainless steel vessel that had an attached thermocouple for controlling the pot furnace heater. Thermocouples were also attached to a reference sample and to the test sample(s) for direct temperature measurement in the molten salt. The reference sample was packaged with the test pieces, as shown in Figures 3 and 4 for the various sample types. After a requisite time at temperature, the package would be removed quickly and quenched in still water. Samples were stored in a refrigerator until used for either testing or subsequent age hardening trials to prohibit natural age hardening.

Age Hardening

Heating for age hardening was similar in method to solution treatment, except that oil was used instead of molten salt. Age hardening was performed by heating samples at 120°C, 150°C and 177°C in heated oil. The threaded cap with the contact thermocouple shown in Figure 5 was used to both hold sample packages in the oil and to measure temperature. Aging times included 10 minutes, 20 minutes, and 30 minutes for short time trials, and 2 hours, 6 hours and 12 hours for longer term aging trials. After aging, test pieces were quenched in water and stored in a refrigerator until testing was conducted.




(a) (b)

Figure 3. Packages showing (a) the reference cylinder with the attached thermocouple, and disc and cylinder samples, and (b) disc and rod samples used for physical property measurements.

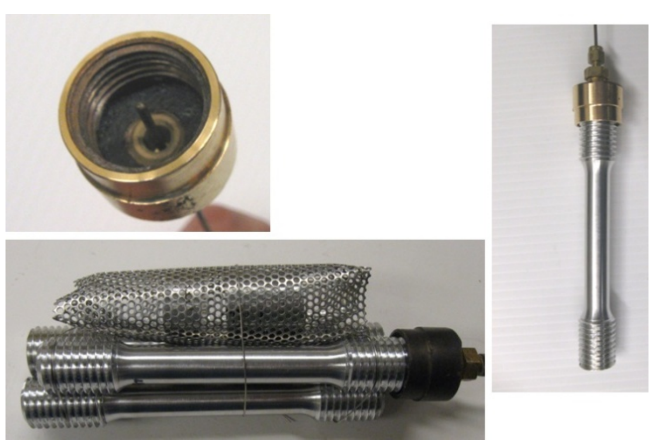


Figure 4. Method used to age harden samples for tension testing. The contact thermocouple is attached to the threaded hat for temperature measurement.

Electrical Resistivity Measurements

Electrical resistivity tests were conducted to characterize the age hardening kinetics. A schematic of the electrical resistivity test cell is shown in Figure 5, and a photograph of the equipment is found in the figure inset.

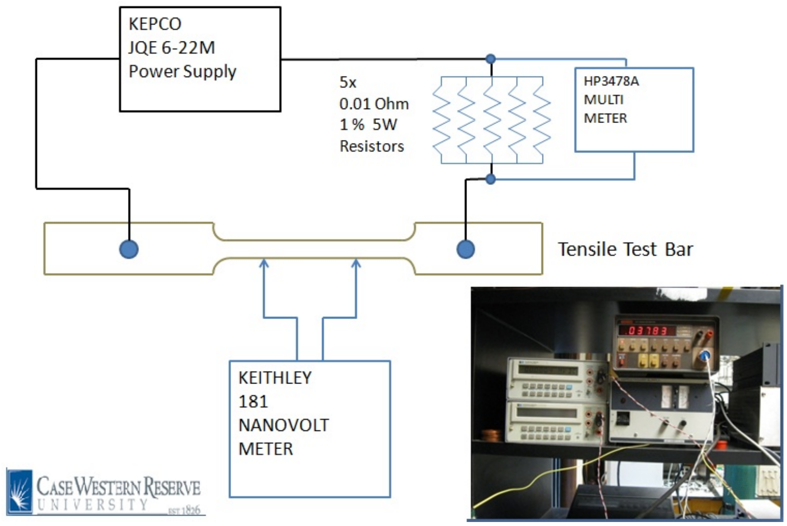



Figure 5. Set up for electrical resistivity measurement at CWRU.

Hardness and Tensile Tests

Hardness and tensile tests were also conducted at CWRU. Elevated temperature tests were conducted within a temperature controlled oven that surrounded the sample and grips. The tensile tests were conducted using an extensometer with a 12.7 mm gage length.

## Results

Time at Temperature Measurements

Typical heating and quenching trial results are shown in Figure 6 for sample 11. The initial temperature of the salt was slightly higher than the aim solutionizing temperature to accommodate the temperature drop upon insertion of the cold sample. The time period started when the sample temperature reached the aim temperature. For sample 11 in Figure 11, the time at temperature was 10 minutes.

Microstructures

Solution treatment trials were conducted by holding samples at either 399°C or 480°C for 5, 10, or 15 minutes. Microstructures are shown in Figures 7 and 8. Clearly, 399°C was insufficient for achieving a solutionized microstructure; grain boundary films have agglomerated into more distinct particles, and particles within grain interiors have also grown by a ripening process, see Figure 7. Figure 8 shows that 480°C was suitable temperature for dissolving alloy particles back into solution. Grain boundaries are relatively free of particles, as are grain interiors. Oxide particles are still present, but these are not responsible for strengthening. In terms of time at temperature, there is little difference between microstructures produced by 5, 10 or 15 minutes. Dissolution occurs rapidly, indicating that temperature is the more important variable, rather than time.

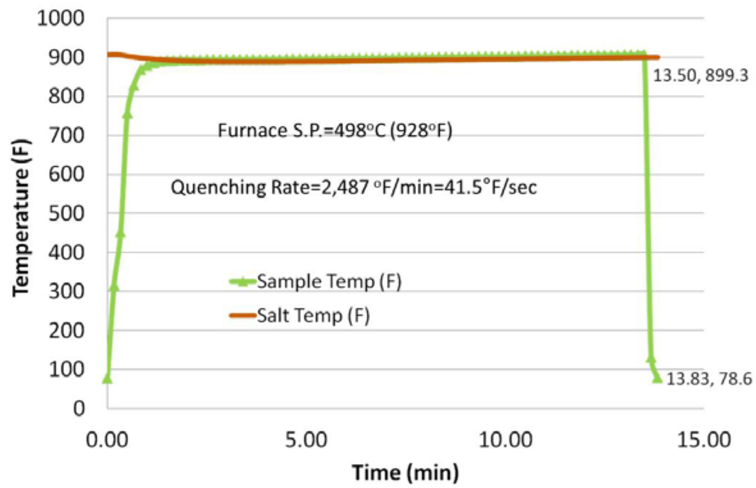



Figure 6. Solution treatment steps of heat up, hold and water quench for sample 11.

<u>Hardness Measurements</u>

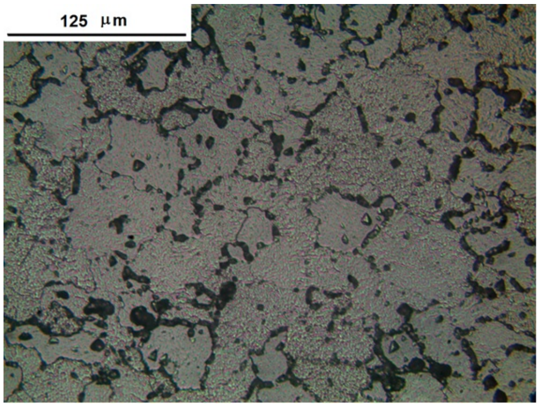
Table III contains hardness measurements for the two solution treatment trial temperatures, as well as the as-received and over-aged conditions. This data shows that the over-aged condition has by far the lowest hardness, HRB 31, and the T651 "as-received" condition has the highest hardness, HRB 91. The temperature of 399°C initiated solution treatment, but was far away from completing the process, producing a hardness of only HRB 57. Holding the over-aged material at 480°C for 5 to 15 minutes resulted in a hardness of HRB 68 to 70. This data provides important metrics for the model phase prediction implementation.

Table III. Hardness Measurements for Solution Treatment Trials

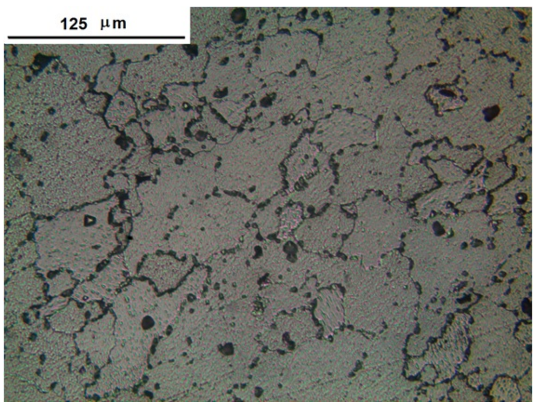
| | | | Hardness Readings(HRB) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample # | Time (min) | Temperature °F | 1 | 2 | 3 | 4 | 5 | Average | Std. Dev. |
| 9 | 15 | 900 | 67 | 69 | 68 | 69 | 69 | 68.4 | 0.89 |
| 10 | 15 | 900 | 66 | 70 | 69 | 68 | 68 | 68.2 | 1.48 |
| 11 | 10 | 900 | 69 | 71 | 70 | 71 | 70 | 70.2 | 0.84 |
| 12 | 5 | 900 | 65 | 68 | 69 | 69 | 68 | 67.8 | 1.64 |
| 13 | 15 | 750 | 53 | 57 | 57 | 58 | 56 | 56.2 | 1.92 |
| 14 | 10 | 750 | 56 | 58 | 58 | 56 | 58 | 57.2 | 1.10 |
| 15 | 5 | 750 | 54 | 58 | 58 | 58 | 58 | 57.2 | 1.79 |
| **As-received** | | | **89** | **91** | **91** | **91** | **91** | **90.6** | **0.89** |
| **Overaged 4hrs@ 600F** | | | **29** | **32** | **32** | **31** | **33** | **31.4** | **1.52** |

<u>Dilation to Determine Phase Change Behavior</u>

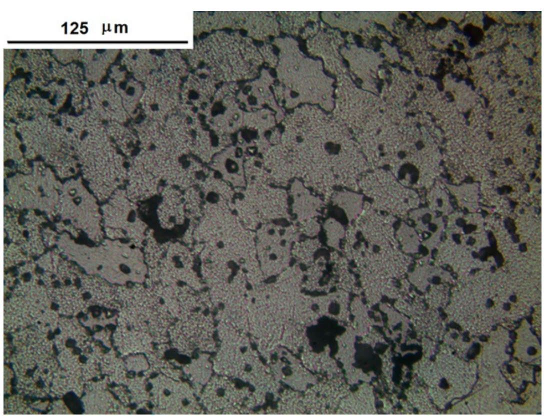
The length of the 63.5 mm long samples was measured before and after the heat treatment using a digital micrometer with six decimals, and the results are found in Table IV. Over-aging resulted in a slight shrinkage in length. Solution treatment of as-received stock, which was in T651 condition, resulted in small growth. From these data, it can be said that growth occurs during solution treatment and aging results in shrinkage, but in both cases the associated strain is small, much less than 0.01%.




(a). Over-aged stock held at 399°C for 5 minutes.

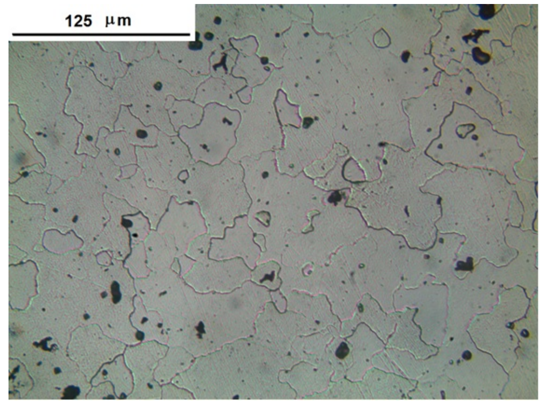



(b). Over-aged bar stock held at 399°C for 10 minutes.

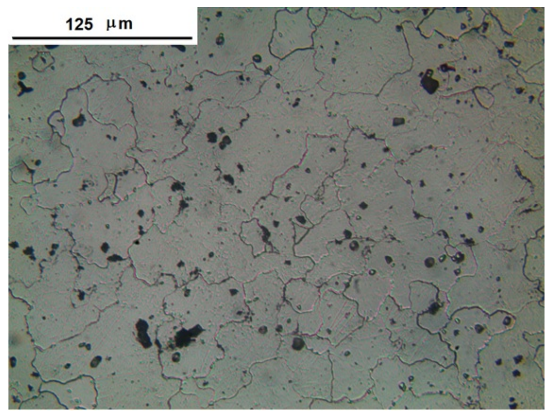



(c). Over-aged bar stock held at 399°C for 15 minutes.

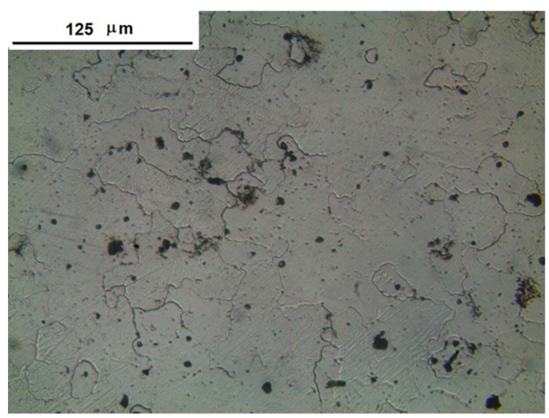
Figure 7. Effect of holding over-aged stock at 399°C .




(a). Over-aged stock held at 900 F for 5 minutes.




(b). Over-aged stock held at 900 F for 10 minutes.




(c). Over-aged stock held at 900 F for 15 minutes.

Figure 8. Solution treatment of over-aged stock at 482°C.

Table IV. Length Changes Due to Heat Treatment

| Heat Treatment Condition | Before Length | After Length | Length Change | Length Strain |
|---|---|---|---|---|
| Over-age As-received stock at 315°C for 4 hours | 63.6575 mm | 63.6473 mm | -0.0102 mm | -0.00016 |
| | 63.6118 mm | 63.5991 mm | -0.0127 mm | -0.00020 |
| Solution Treat As-received Stock at 480° C | 63.6397 mm | 63.6778 mm | +0.0381 mm | +0.00060 |
| | 63.6295 mm | 63.6549 mm | +0.0254 mm | +0.00040 |

Samples machined for tensile testing were also measured before and after heat treatments. Solution treatment of the samples in the as-received condition, T651, resulted in a length strain of 0.0004 ± 0.0002 for 37 samples. Age hardening of these samples resulted in mixed length changes. Figure 9 shows that a small initial growth occurred, but that with aging time the length change was slightly negative. Aging at 177° C resulted in shrinkage strain of approximately -0.0006.

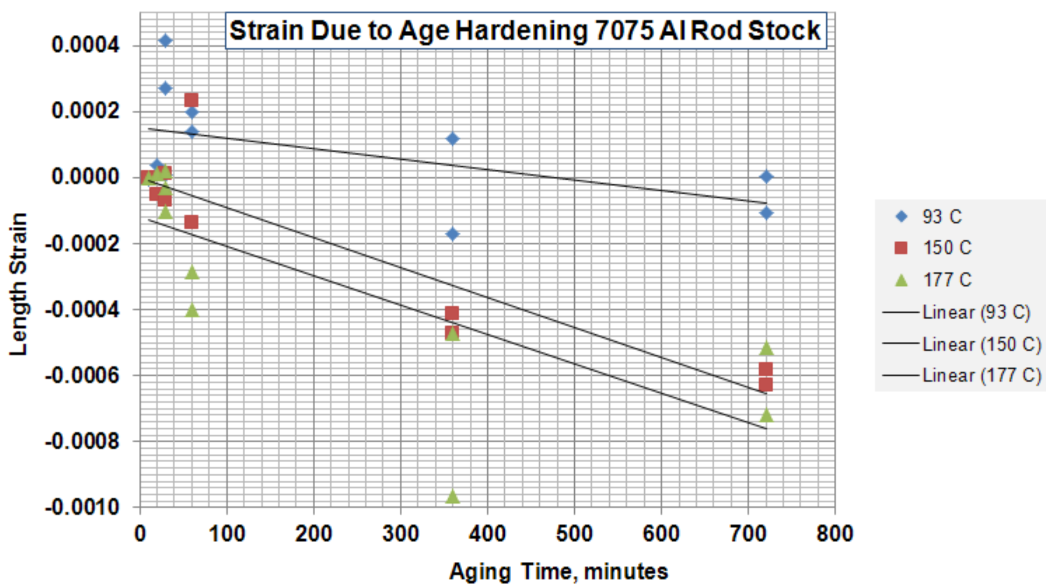


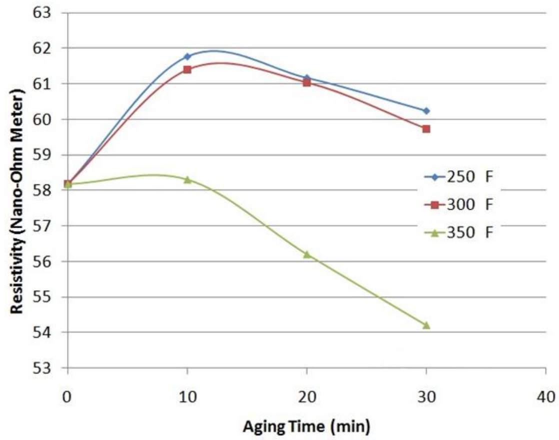

Figure 9. Length strains associated with age hardening of 7075 Al.

Electrical Resistivity to Bracket Phase Transformation Temperatures

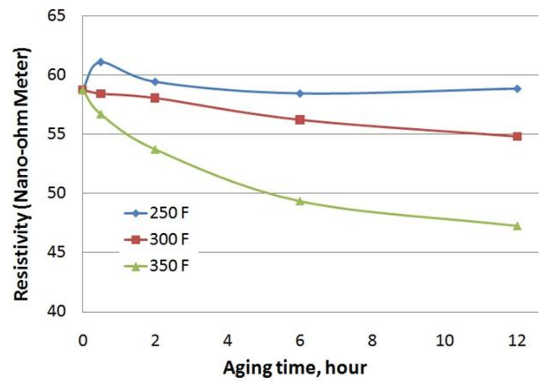
Electrical resistivity measurements were made to bracket temperature boundaries for the solution and aging heat treatments. The resistivity values were 58.20 nano-Ω*m for solution treated samples, 41.77 nano-Ω*m for over-aged samples, and 52.52 nano-Ω*m for as-received samples. During age hardening, the resistivity drops, but not linearly. Figure 10 shows data for short and long age hardening times at temperatures 120°C, 150°C, and 177°C. The basic trends are similar to the length strains with aging. The values initially slightly rise or remain unchanged, and with longer times the resistivity decreases.

Tension Tests and Hardness Measurement Results for Aging Trials

Hardness measurements for identified temperatures and times are shown in Figure 11. Hardness of the solution treated microstructure was HRB 62, which is between the as-received hardness of HRB 90 (T651 condition) and the over-aged hardness of HRB 32. Aging increased the hardness, with 150°C producing the highest measured values, HRB 80.




(a) Short aging time.




(b) Long aging time.

Figure 10. Electrical resistivity of 7075 Al samples in age hardened conditions.

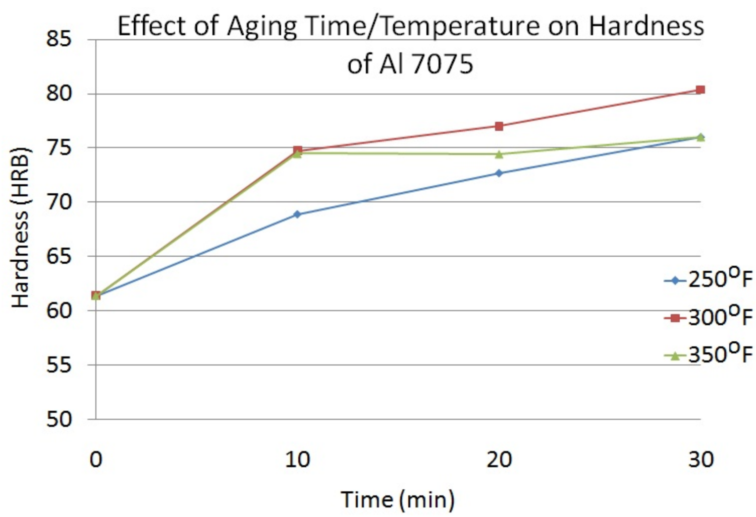



Figure 11. Room temperature hardness measurements for solution treated and age hardened samples.

Room temperature tension test results for samples aged at 120°C, 150°C and 177°C are shown in Figures 12 through 14. The raw data has been shifted so that the elastic portions of the curves are aligned. This eliminates some nonlinear behavior associated with the initial data collection system and allows better comparison of the plastic portions of the tension test data without sacrificing accuracy. The intended use of these data is to fit mechanical parameters used in the internal state variable model described in a later section, and these parameters focus on the plastic behavior of the material.

For samples aged at 120° C for times up to 12 hours, Figure 12 shows that yield and tensile strengths was increased by aging for a longer time. Ductility was decreased as a consequence.

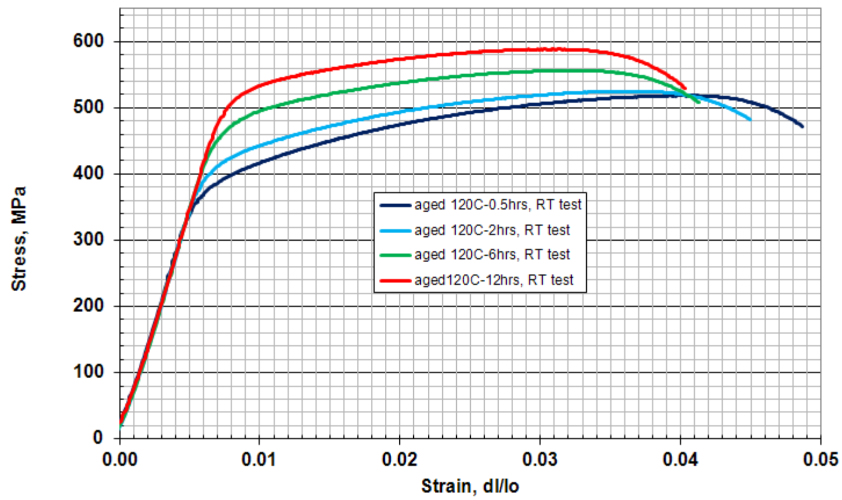



Figure 12. Data for 7075 Al aged at 120°C.

Aging 7075 at 150°C resulted in somewhat different response. Figure 13 shows that the short time of 30 minutes gave the lowest strengths, but that strength and ductility dropped for samples held at 150°C for 12 hours as compared to 6 hours.

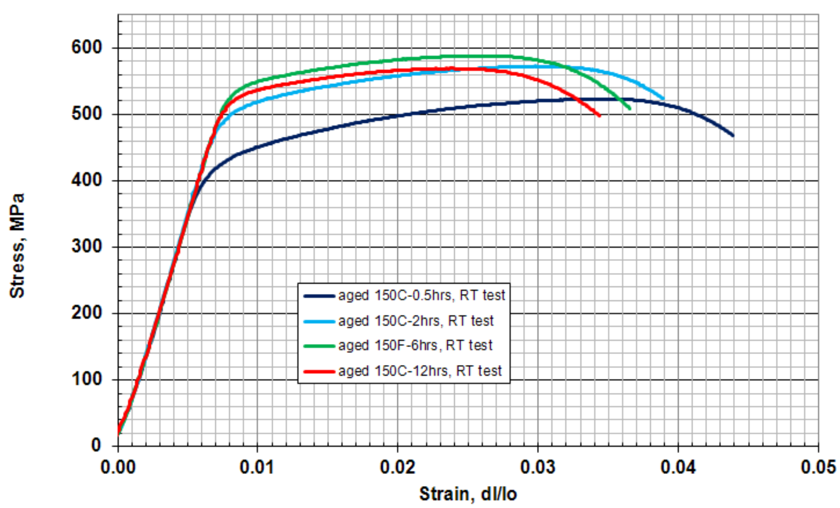



Figure 13. Data for 7075 Al aged at 150°C.

Samples aged at 177°C (350°F) had essentially the same strengths for aging times of 2 hours, 6 hours and 12 hours, as shown in Figure 14. As aging progressed at this temperature, the ductility decreased.

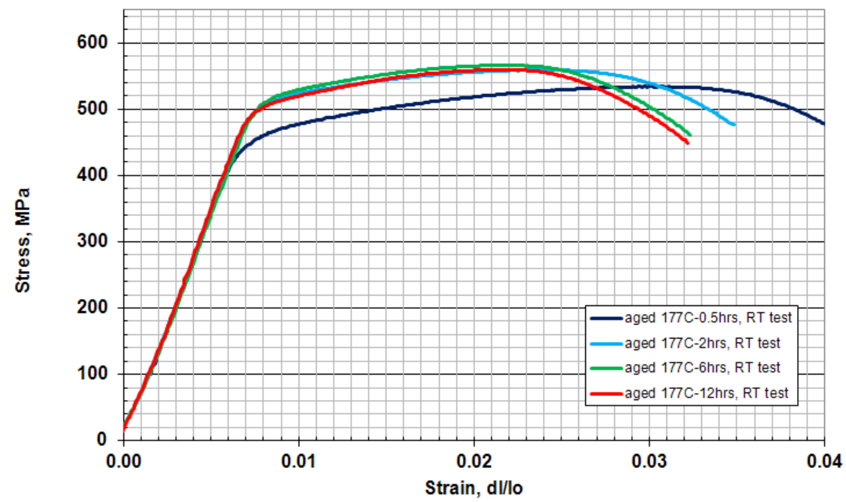



Figure 14. Data for 7075 Al aged at 177°C.

For 30 minutes of aging, the yield strength is increased as the aging temperature is increased from 120°C to 150°C to 177°C. The magnitude of work hardening is decreased as aging temperature is increased. For increased aging times, the strengths achieved by 150°C and 177°C are about the same. For an aging time of 12 hours, the 120°C temperature actually produced equivalent yield strength to the higher aging temperatures, but also the highest tensile strength, most capacity for work hardening, and greatest ductility.

## Summary

A testing program was conducted to develop mechanical and kinetics data that could be used to simulate heat treatment of 7075 aluminum alloy components.

## Acknowledgements

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