10-1-2006

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JMEPEG (2006) 15:601-607
DOI: 10.1361/105994906X136142

1059-9495/$19.00

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(Submitted November 9, 2005)

Aluminum alloys 2099-T6 die forgings, 2099-T83 extrusions, 7075-T7651 plate, 7085-T7452 die forgings, 7085-T7651 plate, and 2397-T87 plate were thermally exposed at temperatures of 180 °C (350 °F), 230 °C (450 °F), and 290 °C (550 °F) for 0.1, 0.5, 2, 10, 100, and 1000 h. The purpose of this study was to determine the effect of thermal exposure on the mechanical properties and electrical conductivity of these alloys. The data shows that higher temperatures and longer exposure times generally resulted in decreased strength and hardness and increased percent elongation and electrical conductivity.

Keywords age hardenable Al alloys, aircraft materials, engineering correlations, overaging, thermal exposure

1. Introduction

The average age of commercial and military aircraft in service today continues to increase the maintenance burden of existing airframes. As maintenance costs and downtime of aircraft increase, the development of new alloys and tempers as direct replacements for existing high-strength but corrosion-prone alloys has gained attention (Ref 1). An increasing number of older aircraft have been retrofitted with new alloys that are developed for increased corrosion resistance without sacrificing strength (Ref 1). The development of these new alloys and tempers as direct replacements in older aircraft is a critical step in extended service of aging aircraft. All the aluminum alloys tested in this study are candidates for use in aircraft or spacecraft as new or direct replacement materials.

Aluminum alloys are used extensively in both the transportation and aerospace industries because they offer better specific strength and resistance to ambient corrosion as compared with other metals (Ref 2). Most of the aluminum alloys developed for aircraft have been the age hardenable 7xxx and 2xxx series alloys.

The 7xxx series alloys, and 7075 in particular, have been the alloys of choice for many aircraft structures. In the peak-aged condition (T6 temper), 7075-T6 offers exceptional mechanical properties. However, 7075-T6 is vulnerable to intergranular corrosion, which can leave the alloy susceptible to stress corrosion cracking (Ref 1). The T7 temper is an overaged condition intended to stabilize the alloy and provide increased corrosion resistance at the expense of decreased strength (Ref 3). This study evaluates the effect of thermal exposure on the tensile strength, hardness, percent elongation at fracture, and electrical conductivity of 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings.

Additionally, the effect of thermal exposure on 2099-T6 die forgings, 2099-T83 extrusions, 2397-T87 plate is studied. These alloys belong to a group of aluminum alloys containing 1.0 to 3.0% lithium that have gained interest in recent years. This interest stemmed from the fact that each 1.0% lithium added to the alloy reduced its density by 3.0% and increased the elastic modulus by approximately 5.0% (Ref 4). These aluminum-lithium (Al-Li) alloys were developed as direct replacements for existing aluminum alloys to reduce the weight of aircraft and other aerospace structures (Ref 5). Typical components for which Al-Li alloys have been envisioned are aircraft structures, spacecraft skins, and liquid oxygen and liquid hydrogen fuel tanks for spacecraft (Ref 5-8).

The aim of this study is to evaluate the response of various aluminum alloys to prolonged thermal exposure at elevated temperatures. The room temperature tensile strength, hardness, and electrical conductivity are measured after exposure at 180 °C (350 °F), 230 °C (450 °F), and 290 °C (550 °F). The thermal exposure conditions are intended to replicate a range of thermal environments encountered in service. A key consequence of prolonged thermal exposure of age hardened aluminum alloys is the potential for a reduction in material strength due to particle coarsening, also referred to as overaging. This study characterizes the effect of thermal exposure on the tensile strength, hardness, percent elongation at fracture, and electrical conductivity of 2099-T6 die forgings, 2099-T83 extrusions, 2397-T87 plate, 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings. This characterization is important in understanding the in-service temperature and exposure time limitations for these alloys.

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Table 1 Alloy compositions (wt.%)

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Zr	Li	Al
2099	0.05	0.07	2.4–3.0	0.1–0.5	0.1–0.5	0.4–1.0	0.1	0.05–0.12	1.6–2.0	bal
2397	0.1	0.1	2.5–3.1	0.1–0.5	0.25	0.05–0.15	0.12	0.08–0.15	1.1–1.7	bal
7075	0.4	0.5	1.2–2.0	0.3	2.1–2.9	5.1–6.1	0.2	...	...	bal
7085	0.06	0.08	1.3–2.0	0.04	1.2–1.8	7.0–8.0	0.06	0.08–0.15	...	bal

Source: Ref 9

Table 2 Aluminum alloys tested

Alloy	Ultimate strength, MPa (ksi)	Yield strength, MPa (ksi)	Elongation, %	Hardness, RB	Conductivity, % IACS
2099-T6 die forgings	529 (76.8)	432 (62.8)	7.6	78	17.5
2099-T83 extrusions	561 (81.5)	502 (72.9)	7.3	80	17.6
2397-T87 plate	473 (68.6)	423 (61.3)	7.5	79	18.4
7085-T7651 plate	519 (75.4)	468 (68.0)	7.8	85	39.8
7085-T7452 die forgings	540 (78.4)	497 (72.1)	9.4	82	41.5
7075-T7651 plate	534 (77.5)	460 (66.8)	7.2	87	33.2

2. The Alloys

The compositions of the aluminum alloys tested are summarized in Table 1 (Ref 9). 2099 and 2397 are both 2xxx series, aluminum-lithium alloys that include copper as the main alloying element. 7075 and 7085 are 7xxx series alloys that contain significantly more zinc and magnesium as compared with 2099 and 2397. Alloys 2397 and 2099 have T_1 precipitates (Al_2CuLi) as the primary strengthening phase. Alloys 7075 and 7085 have η' precipitates ($MgZn_2$) as the primary strengthening phase.

2099 is an aluminum-lithium alloy that has been developed for use in aerospace and high-performance applications requiring high strength and stiffness, low density, superior damage tolerance, corrosion resistance, and weldability and has recently been registered with the Aluminum Association (Ref 8). It offers great improvements over other 2xxx and 7xxx series aluminum alloys resulting in structural weight savings over conventional alloys (Ref 10). For example, 2099-T83 extrusions can be considered for replacement of 2xxx and 7xxx series aluminum alloys in certain applications such as fuselage structures, wing stringers, and other stiffness dominated designs (Ref 8).

Aluminum-lithium 2297 alloy on the other hand is considered as a substitute for the 2124-T851 alloy due to its fivefold enhancement in fatigue life, its 5.0% weight reduction, and its cost efficiency (Ref 5). It is a favorable replacement for aging aircraft to avoid costs in redesign, inspection, and repair (Ref 5). 2397 is similar in composition to 2297, and is also a viable candidate to replace existing alloys in new and aging aircraft.

Aluminum alloy 7075 is used extensively in aircraft structural parts and other highly stressed structural applications (Ref 2). Aluminum alloy 7085 is a new alloy developed by Alcoa (Alcoa, Aerospace Application Engineering, Bettendorf, IA) in response to demands for an aluminum alloy with superior properties throughout large pieces (thick sections). It shows no drop in strengths in section thicknesses up to 30 cm (12 inches) in 7085-T7452 die forgings (Ref 11). This eliminates the need for many intermediate annealing and solution heat treating operations on the part of the fabricators of different products (Ref 11). It can be used for medium-sized structural aerospace parts and for large wing spars, gear ribs, terminal fittings, fuselage frames, bulkheads, engine supports, and ribs (Ref 11).

3. Experimental Procedure

The materials for this experiment were supplied by Alcoa. The average strength, percent elongation at fracture, hardness, and electrical conductivity of the alloys in their as-received conditions are shown in Table 2. The alloys were thermally exposed in these metallurgical conditions. The samples were thermally exposed in air at 180 °C (350 °F), 230 °C (450 °F), and 290 °C (550 °F) for 0.1, 0.5, 2, 10, 100, and 1000 h.

After samples were thermally exposed, they were tested for tensile strength, hardness, and electrical conductivity at room temperature. Figure 1 is a schematic of the tensile specimen dimensions. All test points were performed in triplicate, and unless otherwise specified, the data presented here is the average of three measurements. Hardness tests were performed on the grip sections of the tensile samples using a Rockwell B scale. Conductivity is reported in the International Annealed Copper Standard (% IACS) measured using a Hocking (Hocking NDT Ltd., Hurth, Germany) AutoSigma 3000DL conductivity meter with a 12.7-mm probe. To measure the conductivity, a flat surface was machined on the end of each sample. Tensile tests were conducted on an Instron (Norwood, MA) Model 4505 unit.

4. Results and Discussion

The room temperature tensile strength of all the alloys decreased as a result of thermal exposure. It is also clear that the decrease in tensile strength of 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings was greater than the decrease in tensile strength of 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate at all exposure temperatures. The 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate were generally stronger and remained stronger after thermal exposure. Higher exposure temperatures and longer exposure times resulted in lower ultimate and yield strength values for all alloys. This trend is highlighted in Fig. 2 for the yield strength of 7075-T7651 plate; the yield strength decreases with increased time and temperature. The percent decrease of ultimate and yield strength during the first ten hours of exposure is summarized in Table 3. It should be noted that substantial scatter was observed in the yield strength values for 2099-T83 extrusions at most test points.

After exposure at 180 °C (350 °F), the ultimate and yield tensile strength values for all the alloys changed only slightly for the first 2 to 10 h, but then decreased with increased exposure time. The tensile strength values of the 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings decreased with exposure times greater than 2 h, while those of the 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate decreased after 10 h. The room temperature ultimate and yield strengths after exposure at 180 °C (350 °F) are shown in Fig. 3 and 4, respectively. The as-received (i.e., 0 h of exposure) strength values are provided in the figures for reference.

After exposure at 230 °C (450 °F), there was a more significant decrease in the ultimate and yield tensile strength values for all the alloys as compared with the 180 °C (350 °F) exposure temperature, especially within the first 0.1 h of exposure. The ultimate and yield tensile strength values of the 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate alloys were greater than those of the 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings between 0.1 and 1000 h of exposure at 230 °C (450 °F). The room temperature ultimate and yield strengths after exposure at 230 °C (450 °F) are shown in Fig. 5 and 6, respectively.

Table 3 Percent decrease in ultimate strength (US) and yield strength (YS) for the first ten hours

	180 °C (350 °F)		230 °C (450 °F)		290 °C (550 °F)	
Alloy	US, %	YS, %	US, %	YS, %	US, %	YS, %
2099-T6 die forgings	6	2	25	35	46	66
2099-T83 extrusions	5	5	24	38	49	72
2397-T87 plate	−1	−1	22	31	34	51
7075-T7651 plate	16	20	46	57	53	70
7085-T7452 die forgings	18	25	45	57	57	79
7085-T7651 plate	19	28	47	66	58	79

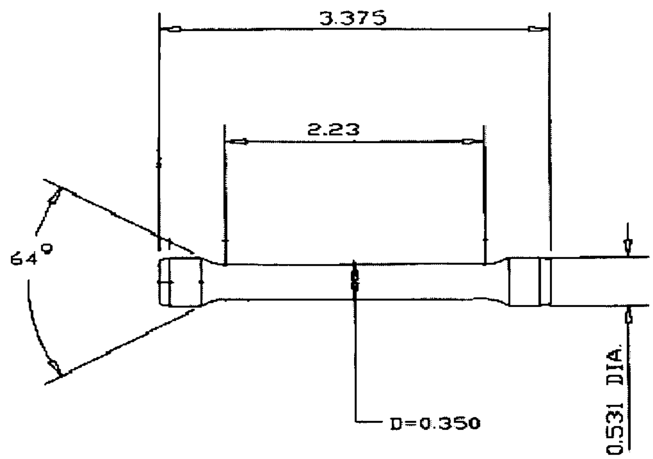

Fig. 1 Tensile specimen (dimensions are in inches, 1 in. is 2.54 cm)

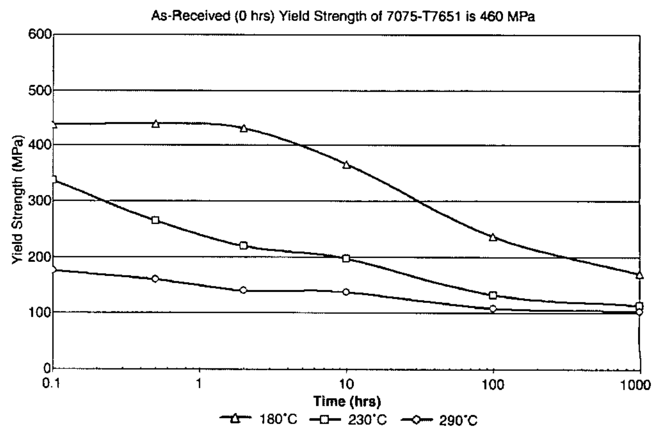

Fig. 2 Room temperature yield strength (YS) of 7075-T7651 after exposure at 180 °C (350 °F), 230 °C (450 °F), and 290 °C (550 °F)

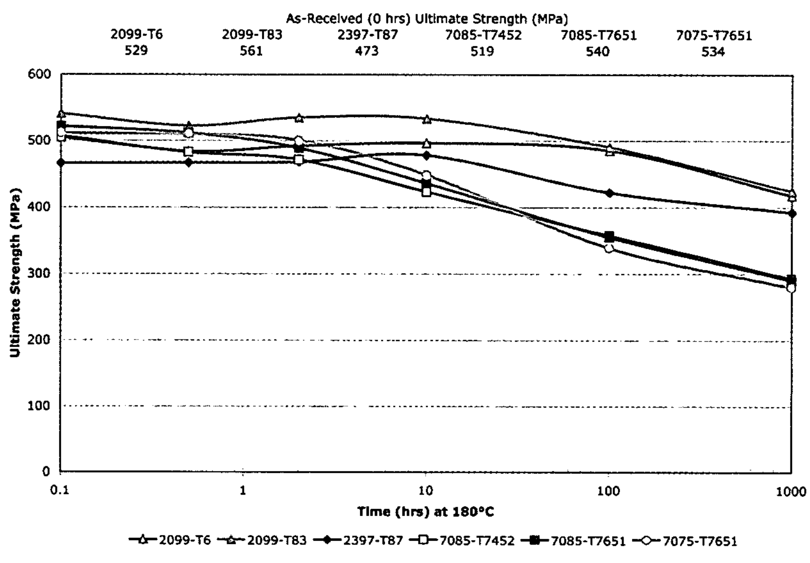

Fig. 3 Room temperature ultimate strength (US) after exposure at 180 °C (350 °F)

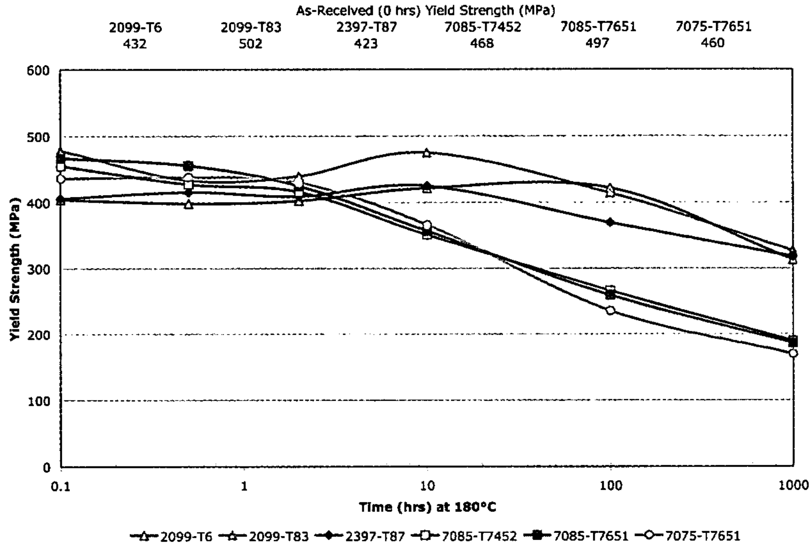

Fig. 4 Room temperature YS after exposure at 180 °C (350 °F). The point at 2 h for 7085-T7452 is the average of only two samples.

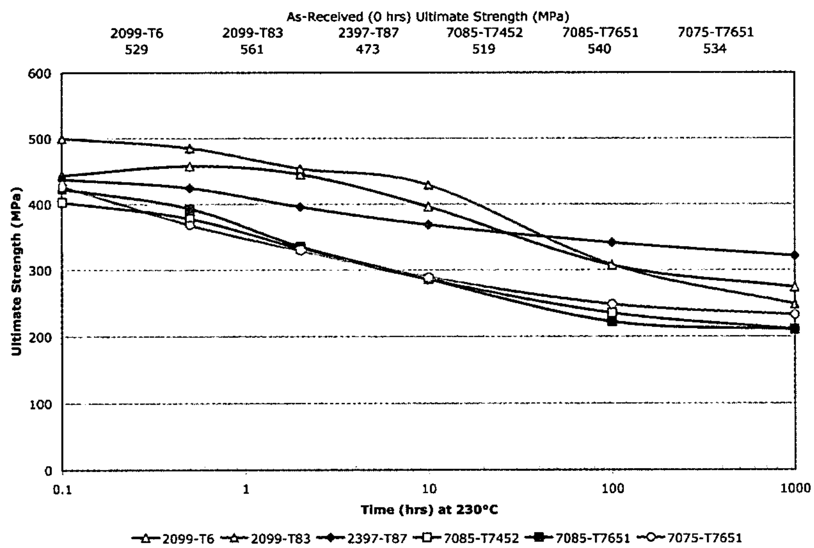

Fig. 5 Room temperature US after exposure at 230 °C (450 °F)

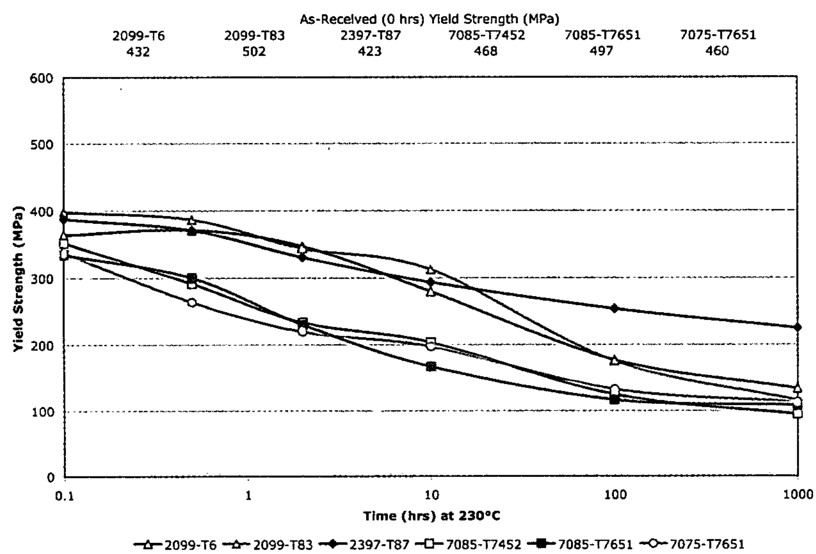

Fig. 6 Room temperature YS after exposure at 230 °C (450 °F)

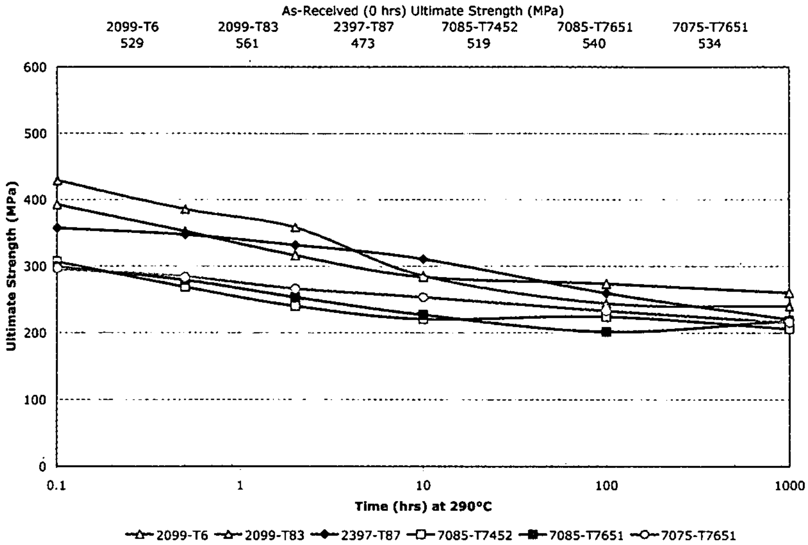

Fig. 7 Room temperature US after exposure at 290 °C (550 °F). The points at 1000 h for 7075-T7651 and 2397-T87 are the average of only two samples.

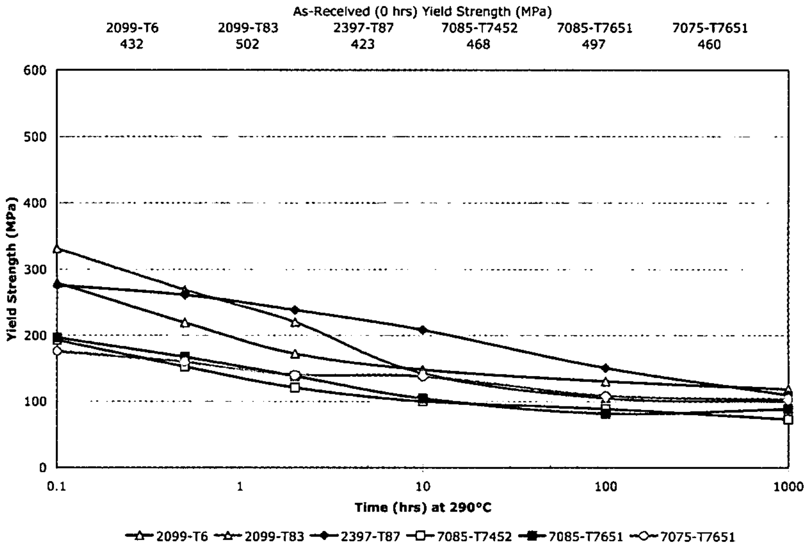

Fig. 8 Room temperature YS after exposure at 290 °C (550 °F). The points at 1000 h for 7075-T7651, 7085-T7651, and 2397-T87 are the average of only two samples.

After exposure at 290 °C (550 °F), the largest reductions in yield and ultimate tensile strength values were found. At this exposure temperature, the most significant reduction in strength occurred within the first 0.1 h, with further reduction in strength being the same or slightly less. For example, the ultimate strength of the 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings decreased by over 40% in the first 0.1 h and then decreased by less than 30% between 0.1 and 1000 h. The room temperature ultimate and yield strengths after exposure at 290 °C (550 °F) are shown in Fig. 7 and 8, respectively.

At the higher exposure temperatures (230 and 290 °C), the tensile strengths of all the alloys decreased only slightly between 100 and 1000 h. This is especially true for the 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings, where the ultimate strength decreased by 3 to 8% between 100 and 1000 h. In other words, at these higher exposure temperatures, the tensile strength fell to a stable level at long exposure times greater than 100 h, suggesting a possible lower limit strength of the material at these exposure temperatures.

At an exposure temperature of 180 °C, the average tensile strength of the 2099-T83 extrusions decreased by up to 18% after 100 h. Other studies on artificial aging of 2099 have shown that plate material can be artificially aged at 180 °C for 50 to 100 h to increase the tensile strength, but that aging times greater than 50 h can cause overaging (Ref 12). The yield and ultimate strengths of the 2099-T83 extrusions decreased by 21 and 14%, respectively, between 100 and 1000 h of exposure at 180 °C. This correlates with other studies on prolonged thermal exposure of 2099-T861 plate, which found that strength decreased from exposure at 177 °C between 100 and 1000 h (Ref 13). However, the yield strength values of the 2099-T83 extrusions at all three exposure temperatures had excessive variation among the triplicate samples.

The hardness of these alloys was measured using the Rockwell B hardness scale. The decrease in hardness was synchro-

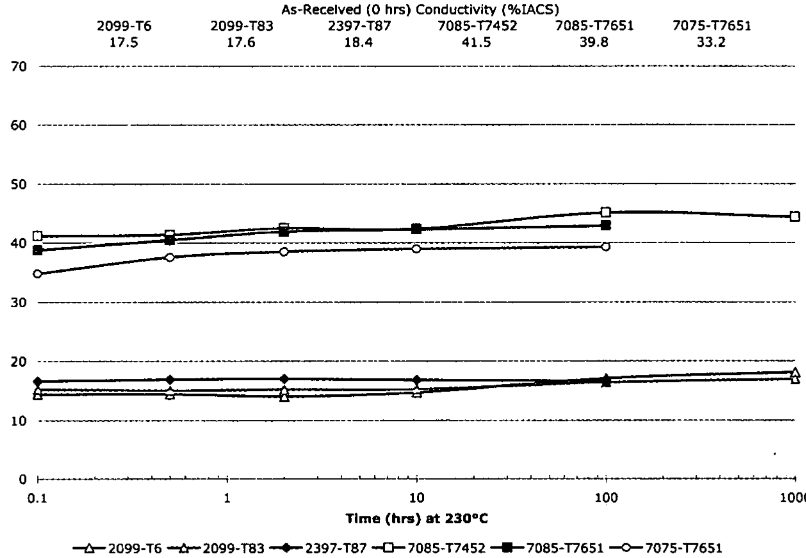

Fig. 9 Room temperature conductivity after exposure at 230 °C (450 °F). The point at 1000 h for 7075-T7651 represents only one sample.

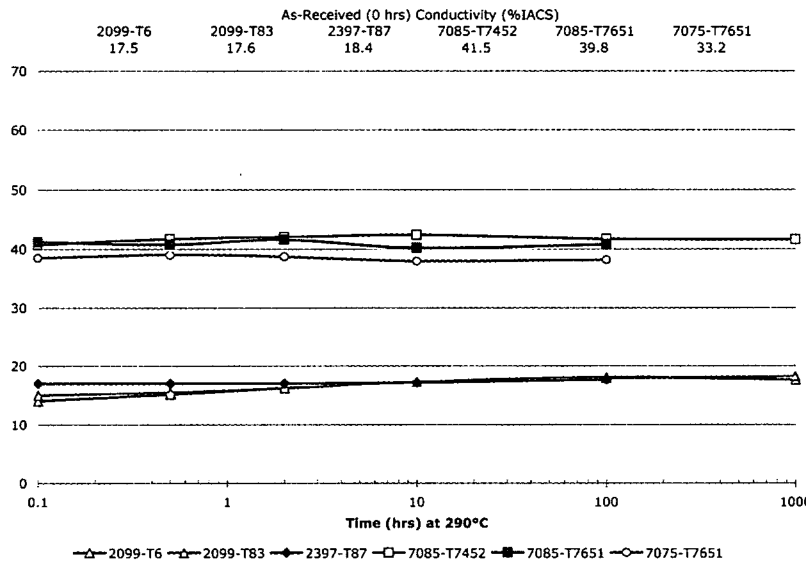

Fig. 10 Room temperature conductivity after exposure at 290 °C (550 °F). The point at 1000 h for 7085-T7452 is the average of only two samples.

Table 4 Correlation between hardness and strength

Alloy	r^2 for yield strength	r^2 for ultimate strength
2099-T6 die forgings	0.913	0.912
2099-T83 extrusions	0.955	0.955
2397-T87 plate	0.958	0.972
7085-T7651 plate	0.936	0.943
7085-T7452 die forgings	0.951	0.952
7075-T7651 plate	0.929	0.932

nous to the decrease in tensile strength. A good correlation between hardness and strength was determined for all the alloys. The square of the correlation coefficient (r^2) between hardness and strength is shown in Table 4. All of the alloys exhibited an r^2 value of greater than 0.9, indicating a high probability of correlation between hardness and tensile strength.

The percent elongation at fracture increased with time and temperature, indicating that the alloys became more ductile with higher exposure temperatures and longer exposure times. This was true for all alloys tested and at all exposure temperatures. 7085-T7452 die forgings and 7085-T7651 plate had the highest percent elongation. The 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings generally had higher percent elongation values as compared with those of the 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate for all tempers.

The electrical conductivity of the 7075-T7651 plate, 7085-T7452 die forgings, and 7085-T7651 plate increased with time and temperature, whereas the electrical conductivity of the 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate remained relatively constant. Electrical conductivity plots are shown in Fig. 9 and 10. The as-received (i.e., 0 h of exposure) conductivity values are provided in the figures for reference.

At the higher exposure temperatures of 230 °C (450 °F) and 290 °C (550 °F), the conductivity of the 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings increased more significantly within the first 0.1 h and changed less over time as compared with the 180 °C (350 °F) exposure temperature.

The conductivity of the 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate were nearly the same and remained relatively constant over time at all exposure temperatures. The change in conductivity of 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate was negligible for the 180 °C (350 °F) exposure temperature. This agrees with previous studies on prolonged thermal exposure of 2099 (Ref 13). At the higher exposure temperatures, the conductivity of 2099-T6 die forgings and 2099-T83 extrusions slightly decreased within the first 0.1 h, and increased only slightly after that, with the increase beginning after 10 h at 230 °C (450 °F) and after 2 h at 290 °C (550 °F). The conductivity of 2397-T87 plate also slightly increased over time at the higher exposure temperatures, but to a lesser extent.

5. Conclusions

Based on the foregoing results and discussion, the following conclusions can be drawn:

- When thermally exposed at 180 °C (350 °F), 230 °C (450 °F), and 290 °C (550 °F), the ultimate and yield tensile strengths of all the alloys decreased over time. This is likely due to overaging because the alloys were in the peak-aged or overaged conditions.
- The tensile strengths of 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings decreased more than those of 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate. The tensile strength values of 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate were higher and remained higher with increased thermal exposure as compared with those of 7075-T7651 plate, 7085-T7651 plate, and 7085-T7452 die forgings.
- After 100 h of thermal exposure, the ultimate and yield strengths decreased only slightly, and each alloy reached a quasi-constant plateau value.
- Higher exposure temperature caused greater decrease in tensile strength. Alloys exposed at 290 °C (550 °F) had much greater reduction in strength.
- A strong correlation between tensile strength and hardness was observed for all the alloys.
- The alloys became more ductile with longer exposure times and higher exposure temperatures. The 7075-T7651 plate, 7085-T7452 die forgings, and 7085-T7651 plate were more ductile than the 2099-T6 die forgings, 2099-T83 extrusions and 2397-T87 plate, as measured by the percent elongation at fracture in tension.
- The electrical conductivity of the 2099-T6 die forgings, 2099-T83 extrusions, and 2397-T87 plate were nearly the same and remained relatively constant over time at all exposure temperatures.
- The electrical conductivity of the 7075-T7651 plate, 7085-T7452 die forgings, and 7085-T7651 plate increased with time, with the increase occurring earlier in time at the higher exposure temperatures.

Acknowledgments

The authors gratefully acknowledge the National Science Foundation and their Research Experiences for Undergraduates program (Grant No. EEC-0353668), and Alcoa for their donation of materials and for machining the tensile bars. Loyola Marymount University and the Naval Air Warfare Center (Patuxent River, MD) are acknowledged for their sponsorship of this research.

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