Composite Conductor

Al-Zr Alloy Wire

Thermal Aging Behavior and Lifetime Modeling for Aluminum-Zirconium Alloy used in ACCR

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Summary

Aluminum-Zirconium alloy that is used as the outer conducting strands in ACCR conductors was subject to an accelerated thermal aging study to look at strength change versus time for different temperatures. The data was used to calibrate an aging model that permits a usable life prediction, where life is defined as 90% strength retention due to thermal aging. The results indicate that at the maximum (continuous) temperature rating of 210°C, there is a projected lifetime of 787 years. Likewise at the maximum (emergency) temperature rating of 240°C, the predicted life is 35 years. There is a large safety factor for use, with the strength change projected to take 1600 hours at 300°C. Note that 3M only rates the ACCR conductor for an accumulated total time of 1,000 hours at the emergency rating temperature of 240°C. The models provide only estimates of longevity for the conditions used in the model. The models used have been used in many fields for similar purposes for many years.

Background

An Aluminum-Zirconium alloy is used for the outer strands of ACCR conductors, and is specified in ASTM B941. This is a heat-resistant aluminum alloy, which is able to operate at elevated temperatures and resist annealing. Thus when the alloy returns to room temperature, the tensile strength is appreciably retained. The temperature ratings for this alloy are for a maximum continuous operating temperature rating of 210°C, and a maximum emergency operating temperature rating of 240°C, where the operating limits are based on 90% strength retention for extended times at the maximum continuous operating temperature rating of 210°C.

The aim of the accelerated aging study reported here is to confirm these rating temperatures and to build and calibrate a life prediction model that provides confidence in the high temperature heat-resistance of the alloy.

Experimental

The aging Study was conducted on 0.175 inch (4.45 mm) diameter wire obtained from Nexans, (Weyburn, SK, Canada). The wire had been drawn to size using 9.8mm (0.39 inch) diameter rod-stock obtained from Lamifil n.v., (Hemiksem, Belgium). Aging was carried out at 240°C, 280°C, 320°C and 400°C, for 1, 10, 100, 1000 hours. Samples were placed in a tube furnace and the temperature was monitored by a thermocouple placed alongside the samples inside the tube furnace. For each condition, four samples were prepared. Once all the samples had been removed and had cooled to room temperature, they were tested in tension to failure using a 10-inch gauge length, and the breaking load recorded. Thereafter the average breaking load of each condition was calculated and then normalized with respect to the non-heat-treated wire.

To build a life prediction model of aging, each temperature was plotted as strength change vs. time and a power–law equation was fitted to the data using Microsoft Excel®

software. These equations were used to extrapolate out in time for each temperature. A limit for reliability or "life" threshold is considered to be a 10% strength drop from the as-received material. Thus, time was calculated for a 90% strength retention for each temperature using the fitted power-law equations. The resulting strength-time-temperature data was used to calibrate an Arrhenius model for aging that produces a 90% strength retention (i.e. usable lifetime). This model takes the form:

k = A*(e^[-E/RT])

k = failure rate (or 1/ time to failure)
A = pre-exponential term
T = Temp
R = Gas Constant

Using a Plot Ln(1/t) vs (1/T) in Kelvins, the terms E/R and A can be determined. This then calibrates the model to determine the lifetime (for 90% strength retention) at various other temperatures.

<u>Results</u>

Table 1 shows the load data for the as-received (i.e. non heat-treated condition).

Sample	Load (lbs)
1	537.4
2	533.2
3	538.8
4	544.9
Average	538.6

Table1. Breaking Load Data for As-Received Wire

Table 2 shows the load data for the heat-treated condition materials.

Time (hrs)	Load (lbs) 240°C	Load (lbs) 280°C	Load (lbs) 320°C	Load (lbs) 400°C
1	505.9	534.8	506.8	490.4
1	531.2	490.1	499.0	489.8
1	507.5	505.2	501.7	504.5
1	510.8	532.4	504.6	480.4
Average	513.8	515.6	503.0	491.3
10	510.0	499.3	484.6	447.3
10	533.3	521.8	509.2	486.8
10	528.6	484.4	505.4	480.9
10	500.8	519.3	522.3	461.7
Average	518.2	506.2	505.4	469.2
100	503.5	512.0	507.0	416.1
100	509.8	518.4	458.7	429.7
100	496.1	503.3	488.6	444.0
100	515.9	487.3	460.5	427.3
Average	506.3	505.2	478.7	429.3
1000	491.7	492.5		
1000	493.5	490.5		
1000	522.2	525.9		
1000	498.4	517.1		
Average	501.4	506.5		

Table 2. Breaking Load data for heat-treated (aged) wire

Data for each temperature is shown in Figure 1, where the average strength is normalized by the non heat-treated strength expressed as a percentage. This is plotted versus time for each temperature. Typically, one hour of aging shows a shift in strength but thereafter for 240°C and 280°C the strength remains constant. However, the 320°C and 400°C data show progressively larger downward shifts in strength with time exposed to temperature.

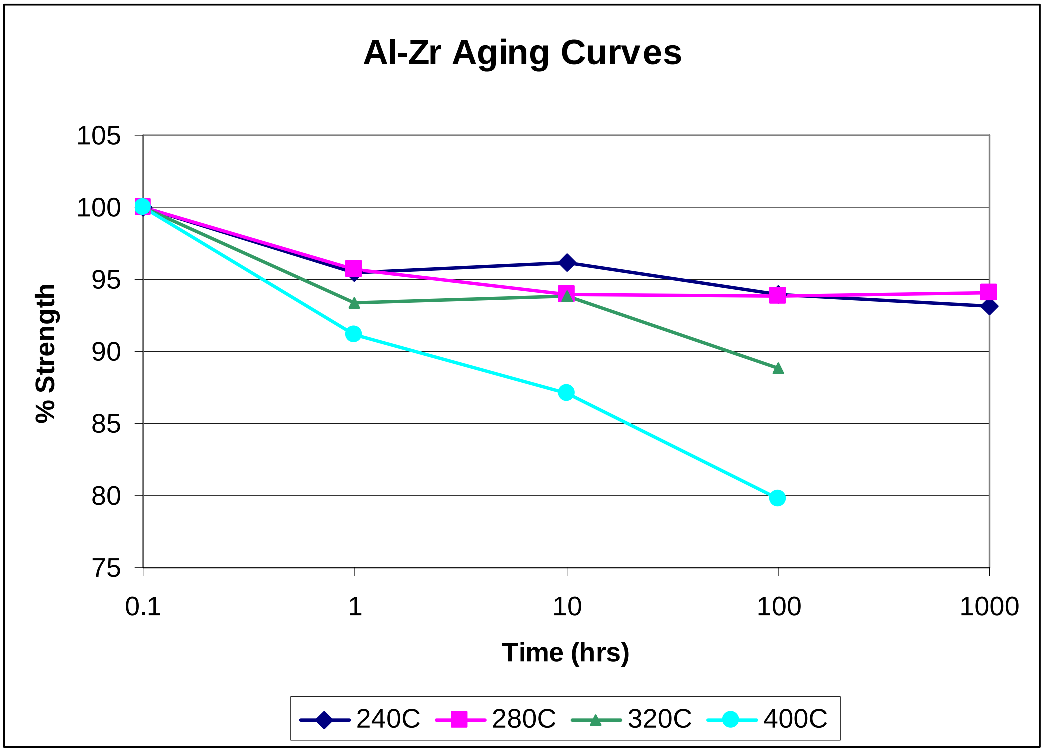

Figure 1. Aging Curves of Normalized Average Strength (%) vs. Time for Al-Zr wire at 240°C, 280°C, 320°C and 400°C.

For each temperature, Power Law fits are made to the data to permit extrapolation to longer times (Figures 2, 3, 4 & 5). Note 40 years is approximately 350,000 hours.

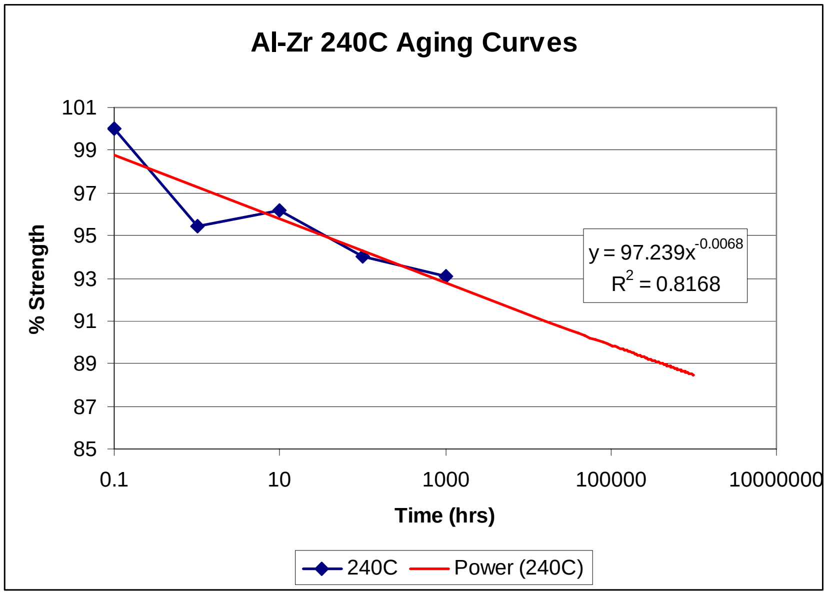

Figure 2. Power-law fit to 240°C data.

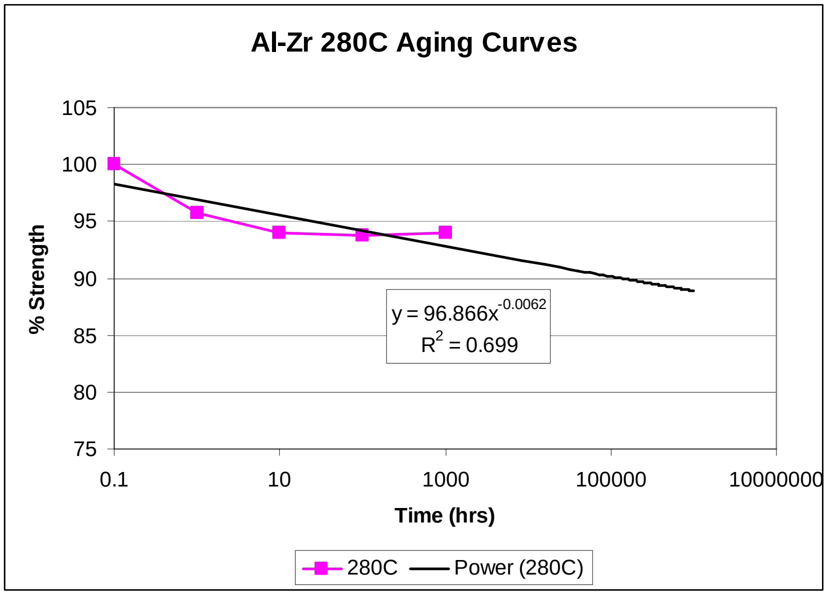

Figure 3. Power-Law fit to 280°C data.

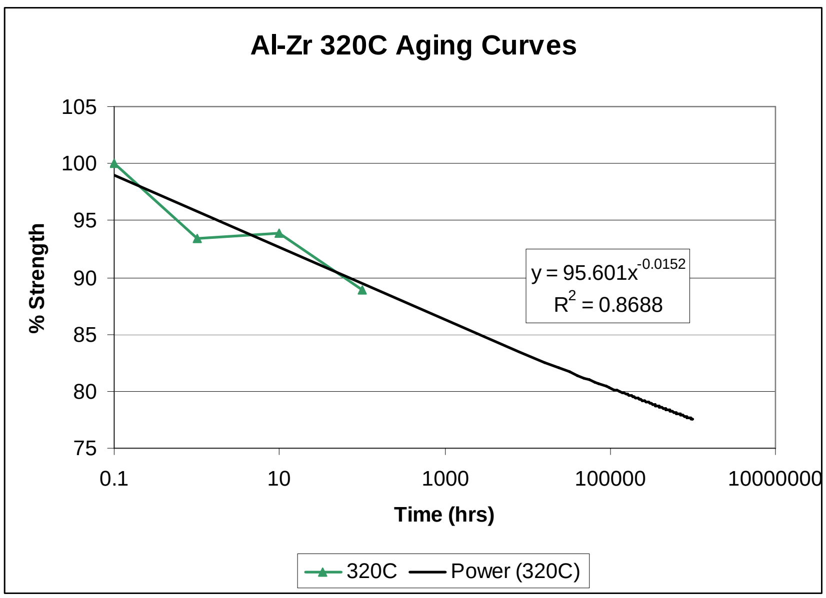

Figure 4. Power-Law fit to 320°C data.

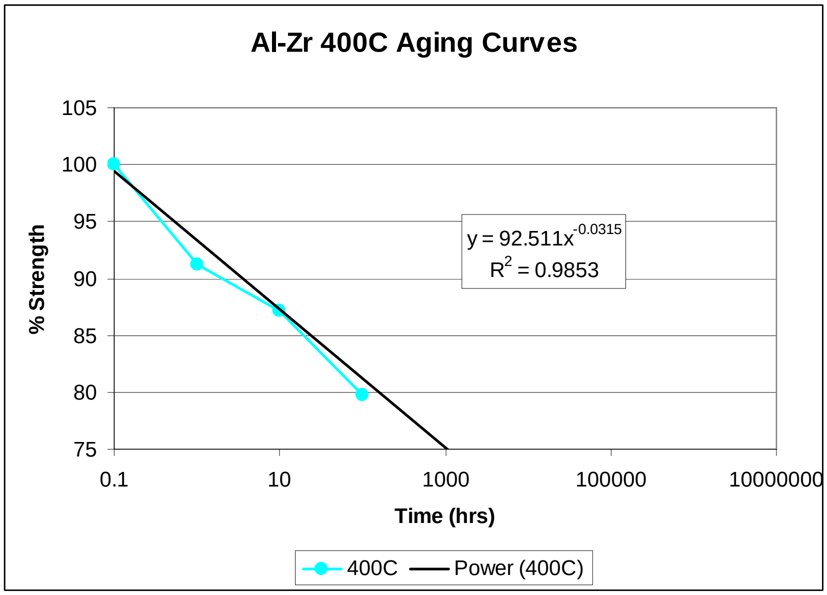

Figure 5. Power-Law fit to 400°C data.

Life Prediction Modeling

Using the power law equations from the previous section, times are computed for a 90% strength retention (ZTACIR conductor which has the same alloy uses this as threshold for rating the high temperature aluminum alloy). That is the strength drops to 90% of the starting strength. The resulting data is shown in Table 3.

T/°C	x (time)/hrs	y (% Strength)	Time (years)
240	90,000	90.0	10.3
280	150,000	90.0	17.1
320	55	90.0	0.0
400	2.4	90.0	0.0

Table 3. Temperature-time predictions for 90% strength retention

It is assumed that thermal aging of these alloys obeys an Arrhenius Equation of the form:

k = A*(e^[-E/RT])

k = failure rate (or 1/ time to failure of X%)
A = pre-exponential term
T = Temp
R = Gas Constant

The data from Table 3 is processed so that a plot can be constructed of Ln(1/t) [t in hours] vs (1/T) in [T in Kelvins]. This is shown in Table 4. The graphical construction is shown in Figure 6, which solves for the parameters E/R and A.

T/°C	t (hrs)	1/t	Ln(1/t)	T/K	1/T
240	90,000	1.11111E-05	-11.40756	513	0.001949318
280	150,000	6.66667E-06	-11.91839	553	0.001808318
320	55	0.018181818	-4.007333	593	0.001686341
400	2.4	0.416666667	-0.875469	673	0.001485884

Table 4. Data for plotting of Ln(1/t) [t in hours] vs. (1/T) in [T in Kelvins]

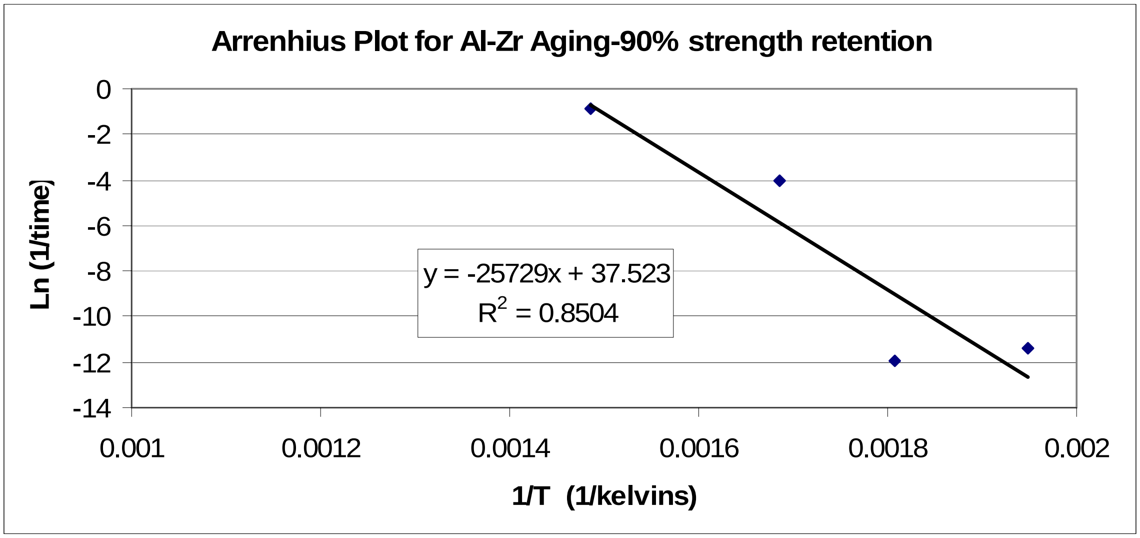

Figure 6. Arrenhius Plot for thermal aging of Al-Zr alloy for 90% strength retention, which also shows the linear fit to the data

From the graph, the values for the parameters are:

E/R	-25729
A	1.977E+16

These parameters are used to extrapolate to other temperature-time combinations that lead to a 90% strength retention. A selection of these is shown in Table 5.

T/°C	T/K	k	t (time-hours)	t (yrs)
300	573	0.0006241	1,602	0.2
400	673	0.4929675	2.03	0.00
500	773	69.296512	0.01	0.00
250	523	8.529E-06	117246	13.38
240	513	3.269E-06	305,895	34.9
238	511	2.686E-06	372,240	42
210	483	1.451E-07	6,893,925	787
200	473	4.704E-08	21,260,232	2,427
150	423	7.587E-11	13,181,222,312	1,504,706
100	373	2.183E-14	45,811,317,285,176	5,229,602,430
20	293	1.444E-22	6,924,042,231,203,310,000,000	790,415,779,817,730,000

Table 5. Temperature-time combinations for 90% strength retention

Thus there is a 40-year survival as defined by 90% strength retention at a temperature of 238°C. This is above the continuous use temperature rating of 210°C. At the temperature of 210°C survival time is 787 years. At the emergency temperature rating of 240°C the survival is 35 years. 3M recommends an accumulated 1000 hours at this temperature for the ACCR conductor, thus this seems to err on the side of caution. In the case of the conductor being operated above its design temperatures, the survival is 1600 hours at 300°C. again suggesting there is considerable conservatism in the temperature ratings.

Conclusion

Aluminum-Zirconium alloy that is used as the outer conducting strands in ACCR conductors was subject to an accelerated thermal aging study to look at strength change versus time for different temperatures. The data was used to calibrate an aging model that permits a usable life prediction, where life is defined as 90% strength retention due to thermal aging. The continuous maximum temperature rating of 210°C gives a projected lifetime of 787 years for 90% strength retention. A similar strength change at 240°C (emergency temp) is projected to take 35 years. There is a large safety factor with the same strength change projected to take 1600 hours at 300°C. Note that 3M only rates the ACCR conductor for an accumulated total time of 1,000 hours at the emergency rating temperature of 240°C. The models provide only estimates of longevity for the conditions used in the model. The models used have been used in many fields for similar purposes for many years.

Acknowledgement

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