Aging Optimization of Aluminum-Lithium Alloy L277 for Application to Cryotank Structures

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Compared with aluminum alloys such as 2219, which is widely used in space vehicle for cryogenic tanks and unpressurized structures, aluminum-lithium alloys possess attractive combinations of lower density and higher modulus along with comparable mechanical properties and improved damage tolerance. These characteristics have resulted in the successful use of the aluminum-lithium alloy 2195 for the Space Shuttle External Tank, and the consideration of newer U.S. aluminum-lithium alloys such as L277 and C458 for future space vehicles. These newer alloys generally have lithium content less than 2 wt. % and their composition and processing have been carefully tailored to increase the toughness and reduce the mechanical property anisotropy of the earlier generation alloys such 2090 and 8090.

Alloy processing, particularly the aging treatment, has a significant influence on the strength-toughness combinations and their dependence on service environments for aluminum-lithium alloys. Work at NASA Marshall Space Flight Center on alloy 2195 has shown that the cryogenic toughness can be improved by employing a two-step aging process. This is accomplished by aging at a lower temperature in the first step to suppress nucleation of the strengthening precipitate at sub-grain boundaries while promoting nucleation in the interior of the grains. Second step aging at the normal aging temperature results in precipitate growth to the optimum size.

A design of experiments aging study was conducted for plate and a limited study on extrusions. To achieve the T8 temper, Alloy L277 is typically aged at 290°F for 40 hours. In the study for plate, a two-step aging treatment was developed through a design of experiments study and the one step aging used as a control. Based on the earlier NASA studies on 2195, the first step aging temperature was varied between 220°F and 260°F. The second step aging temperatures was varied between 290°F and 310°F, which is in the range of the single-step aging temperature. For extrusions, two, single-step, and one two-step aging condition were evaluated.

The results of the design of experiments used for the T8 temper as well as a smaller set of experiments for the T6 temper for plate and the results for extrusions will be presented. The process of selecting the optimum aging treatment, based on the measured mechanical properties at room and cryogenic temperature as well as the observed deformation mechanisms, will be presented in detail. The implications for the use of alloy L277 in cryotanks will be discussed.

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Outline

- Aluminum-Lithium Alloys
- Cryogenic Fracture Toughness (CFT) of Al-Li Alloys
  - Mechanisms of toughness improvements
- Design of Experiments (DOE) for Aging Optimization of L277
  - Effects of Two-Step Aging on Strength/Toughness
  - Aging Cycle Recommendations
- Summary

Alloy Compositions (wt. %)

Alloy	Density (lb/in.^{3})	Cu	Li	Mg	Zn	Mn	Zr	Ag
2195	0.0975	4.0	1.0	0.4			0.11	0.4
L277	0.0975	3.5	1.0	0.4		0.35	0.10	0.4
C458	0.0945	2.7	1.8	0.3	0.6	0.25	0.08	
2090	0.093	2.7	2.2				0.12	
8090	0.092	1.2	2.4	0.95			0.11	
2219	0.103	6.3				0.30	0.18	

Cryogenic Fracture Toughness Improvements

- **Extrinsic Mechanism (Rao and Ritchie, UC Berkeley, Ca. 1990)**
  - –Certain Al-Li Alloys (2090-T81, 8090-T8 Etc.) Exhibit a Significant Increase in L-T and T-L Cryogenic Fracture Toughness
  - –Attributed to Delamination Toughening
  - –Accompanied by a Slight Decrease in S-L and S-T Toughness
  - –Transgranular Microvoid Coalescence Remains As the Fracture Mechanism With Decreasing Temperature
- **Intrinsic Mechanism (Chen and Stanton, NASA MSFC, 1996)**
  - –Suppression of Sub-grain Boundary Precipitation of T_1
    - ✓Increase Driving Force for Homogeneous Nucleation in the Grains by Decreasing Aging Temperature. Second Step Aging in the "Peak Aging" Range Results in Precipitate Growth to the Optimum Size.
  - –General Increase of Ductility and Strain Hardening Rate With Decreasing Temperature.

DOE for Aging Optimization of L277 Plate

- 2^4 Full Factorial Experiment With Center Point
  - 8 Aging Trials and Two Center Points Tested (240°F/48 hrs + 290°F/32 hrs and 240°F/48 hrs + 290°F/40 hrs)
  - Solution Heat Treat and Stretch to be Held Constant
  - Smaller Test Plan Used for –T6 Validation

- Temperature Selection Rationale
  - First Step Aging Treatment at Temperatures Between 220°F and 260°F to Promote Homogeneous Nucleation of T_1 Which Improves Toughness at Cryogenic Temperature, While Not Impacting Other Properties
  - Second Step Aging Treatment Is Necessary to Obtain the Optimum Combination of Strength and Toughness Within Practical Aging Times
    - ✓ 290°F and 310°F for –T8
    - ✓ 325°F and 350°F for –T62

DOE Details for L277 Plate

- **Materials**
  - All Specimens for T8 Aging Came From a Single Lot of L277 Material Rolled to 1.8 Inch Thickness and Processed at the Mill to the T3 Temper.
  - All Specimens for T62 Aging Came from a Single Lot of L277 Material Rolled to 0.85 Inch Thickness and Provided in the F Temper
  - Specimen Orientation of All Tensile Specimens was LT and All Toughness Specimens was T-L Orientation
- **Processing**
  - T8 Temper (Panels T01 through T20) - Aged to the Specified Parameters
  - T62 Temper (Panels F01 through F09) - Solution Heat Treat (975°F/0.5 hr) and Aged to the Various Specified Parameters
- **Testing**
  - Tests Conducted at Room and Cryogenic (-320°F) Temperatures
  - Tensile Tests Performed in Triplicate and Toughness Tests in Duplicate
  - J_{IC} Toughness Tests Run to be Consistent With C458 Testing

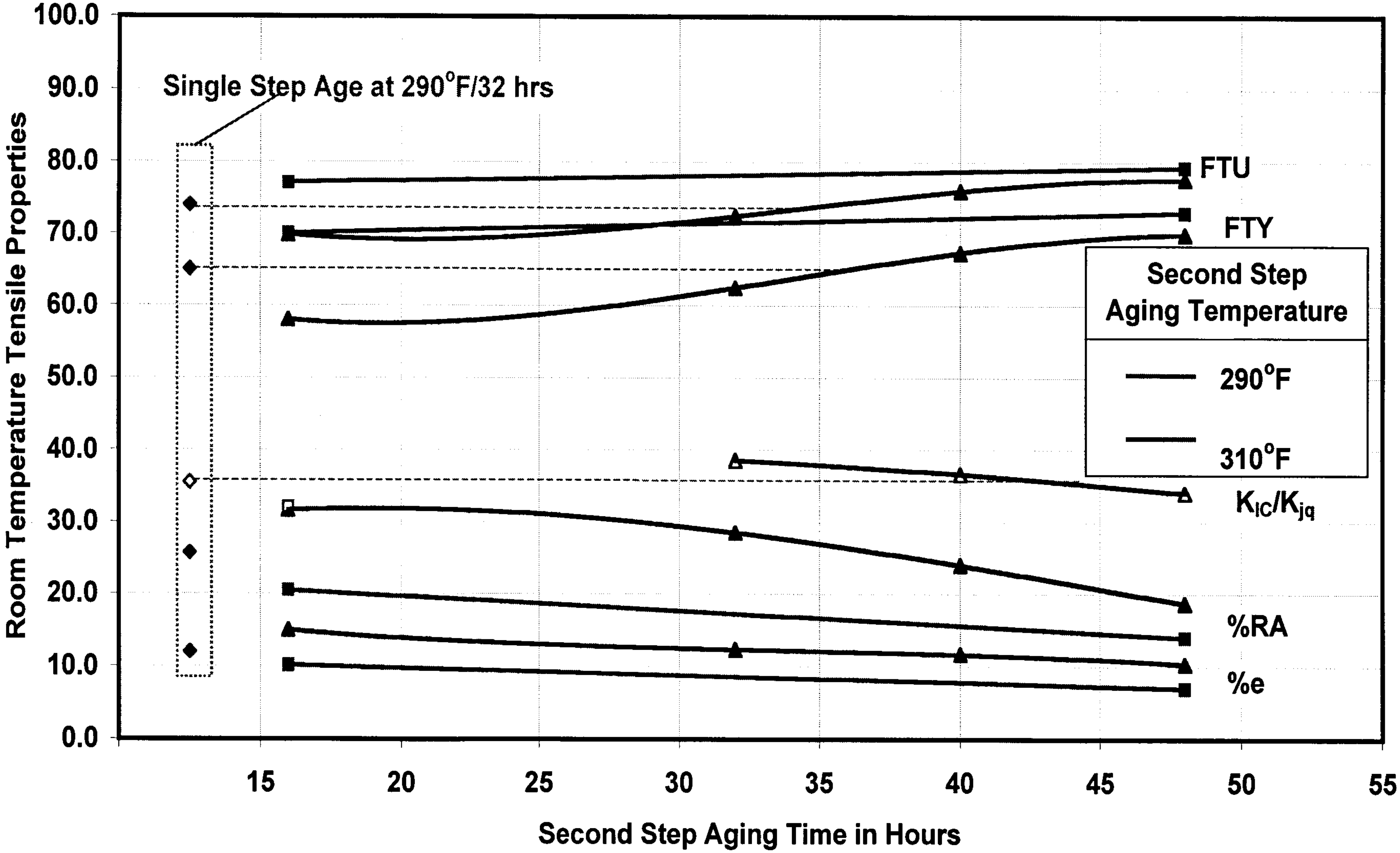
Aging Parameters for L277-T8 Plate

Plate	Temper	Aging Parameters			
		First Step		Second Step	
		Temp, °F	Time, hrs	Temp, °F	Time, hrs
T01	-T8	220	24	290	16
T02	-T8	220	24	290	48
T03	-T8	220	24	310	16
T04	-T8	220	24	310	48
T05	-T8	220	96	290	16
T06	-T8	220	96	290	48
T07	-T8	220	96	310	16
T08	-T8	220	96	310	48
T09	-T8	260	24	290	16
T10	-T8	260	24	290	48
T11	-T8	260	24	310	16
T12	-T8	260	24	310	48
T13	-T8	260	96	290	16
T14	-T8	260	96	290	48
T15	-T8	260	96	310	16
T16	-T8	260	96	310	48
T17	-T8	240	48	290	32
T18	-T8	240	48	290	40
T20	-T8	290	32	n/a	n/a

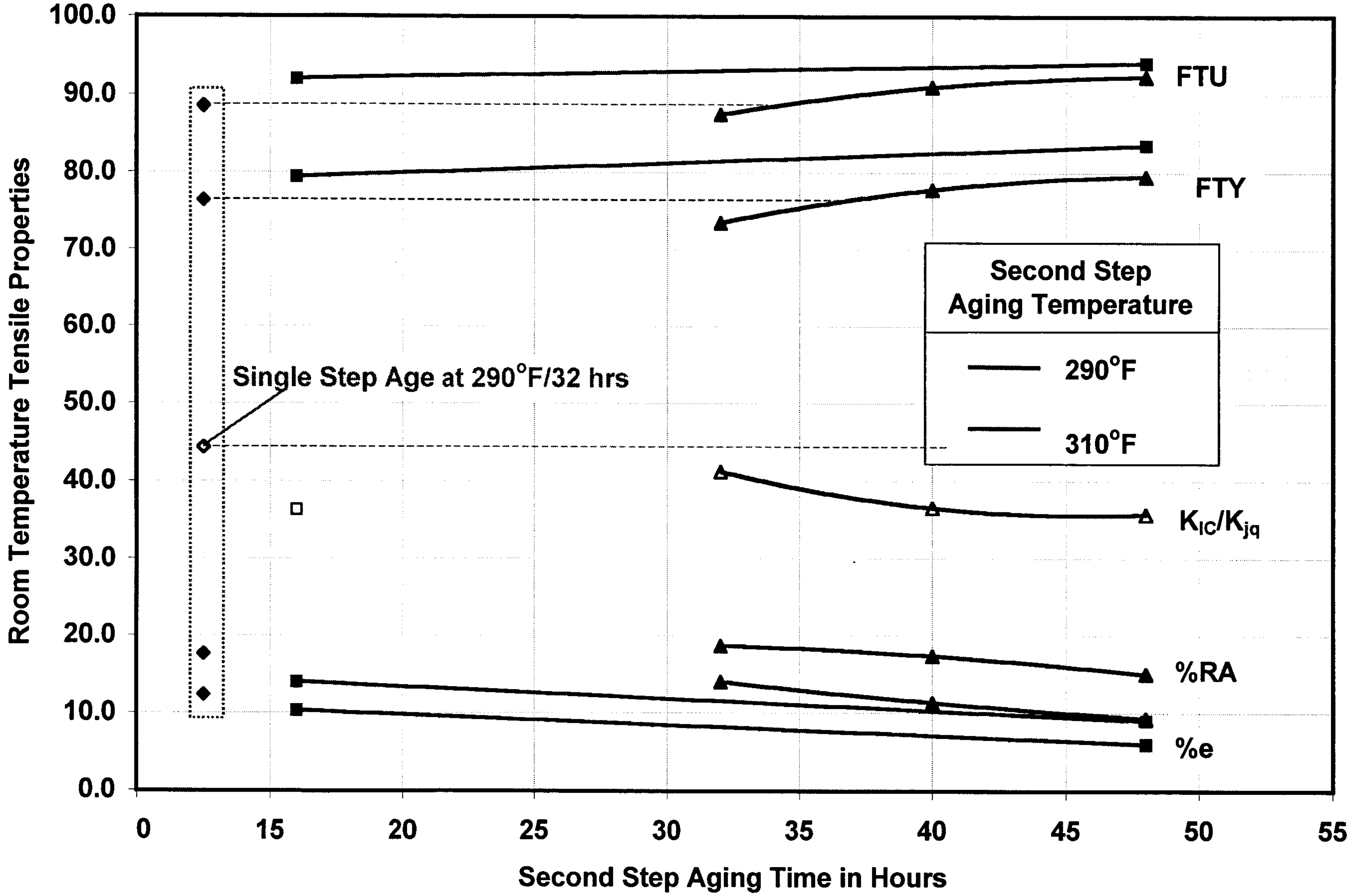
Effects of Aging on the Properties of L277-T8 Plate

Plate	Aging Parameters				Tensile Properties								Fracture Toughness			
	First Step		Second Step		RT				-320 F				RT		-320°F	
	Temp, °F	Time, hrs	Temp, °F	Time, hrs	FTU	FTY	%e	%RA	FTU	FTY	%e	%RA	K_{IC}	K_Q	K_{IC}	K_Q
T01	220	24	290	16	68.2	55.1	16.3	34.0								
T04	220	24	310	48	79.2	73.0	6.7	14.0								
T06	220	96	290	48	77.9	70.5	10.0	15.7								
T07	220	96	310	16	77.5	70.6	10.7	22.0								
T10	260	24	290	48	77.3	69.5	10.7	21.7	92.3	79.5	9.3	15.0	34.0	30.8	35.7	
T11	260	24	310	16	76.8	69.5	9.7	19.0	92.1	79.5	10.3	14.0	32.1	28.4	36.4	
T12	260	24	310	48												
T13	260	96	290	16	71.6	61.1	13.7	29.3								
T16	260	96	310	48	79.3	73.0	7.3	14.0								
T17	240	48	290	32	72.5	62.5	12.3	33.7	87.4	73.5	14.0	18.7		33.7	38.8	
T18	240	48	290	40	76.0	67.4	11.7	24.0	91.0	77.8	11.3	17.3		34.6	36.6	38.9
T20	290	32	n/a	n/a	74.0	65.0	12.0	25.7	88.5	76.4	12.3	17.7		30.7		41.2

Aging Curves for L277 Plate (RT Properties)



Aging Curves for L277 Plate (-320 F Properties)



Effects of Aging on the Properties of L277-T6 Plate

Plate	Aging Parameters				Tensile Properties								Fracture Toughness			
	First Step		Second Step		RT				-320 F				RT		-320°F	
	Temp, °F	Time, hrs	Temp, °F	Time, hrs	FTU	FTY	%e	%RA	FTU	FTY	%e	%RA	K_{IC}	K_Q	K_{IC}	K_Q
F1	260	24	325	24	65.3	56.0	13.7	34.7	79.3	66.1	16.3	32.3		26.7		33.3
F2	300	24	325	24	66.4	56.7	13.0	35.3								
F3	260	24	350	24	64.8	56.1	12.0	32.3								

Discussion of Aging Effects for L277 Plate

- **T8 Aging**
  - **Second Step Aging of 290°F/32 Hrs (T01 and T13) Results in an Underaged Condition with Low Strength and High Elongation**
  - **Second Step Aging of 310°F/48 Hrs (T04 and T16) Results in Good Strength but Lower Elongation**
  - **Other Aging Cycles Result in Good Strength/Good Elongation**
  - **There is no Benefit to Two-Step Aging in Terms of Improving Cryogenic Toughness**
- **T6 Aging**
  - **Varying Second Step Aging Between 325°F and 350°F Did Not Result in Significant Strength variations**

Recommended Aging Parameters for L277 Plate

Selected L277-T62 Plate Aging Practice

First Step Age:	**260°F/24 Hours**
Second Step Age:	**325°F/24 Hours**

Selected L277-T8 Plate Aging Practice

Single Step Age:	**290°F/40 Hours**

Summary

- Two Step Aging of L277 Plate Product Resulted in Higher Cryogenic Toughness for
  - T6 and not T8
- The observation can be explained on the basis of
  - Relatively low Li content in L277
  - The need for stretch for aging response in the T8 temper
- With the limited number of toughness tests, toughness was generally observed to increase with increasing tensile elongation and reduction of area, suggesting the usefulness of tensile tests for screening heat treatments
- For space vehicle cryotank applications, one could selected an optimized aging cycle for the application rather than the product form.