LI MATERIAL TESTING- FERMILAB ANTIPROTON SOURCE LITHIUM COLLECTION LENS*

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Abstract

The lithium collection lens is a high current (greater than 0.5 MA), pulsed device used to focus antiprotons just downstream of the production target. Pre-mature failure of these lenses has led to extensive efforts to understand the cause of the failures. One of the main unknowns is the structural behavior of lithium under such extreme loading conditions. Lithium can be categorized as a soft or "plastic" solid with relatively low modulus of elasticity and yield strength. Very little is available on its nonlinear and viscoplastic (rate dependent) structural properties. Tests were conducted to determine the rate dependent tensile behavior and creep response of lithium at various temperatures. Results of these tests are presented.

INTRODUCTION

The FNAL collection lens operates by passing a large axial current through a solid lithium (Li) cylinder 1 cm in radius. This produces a strong magnetic field proportional to the radius and has the advantage of focusing in both transverse planes. The 1 cm lens was designed for a focusing gradient of 1000 T/m, but due to premature failure it is currently operated at reduced gradients. At a lower gradient of around 745 T/m, the lens can last for millions of pulses and have an operational life greater than six months. The downside is lower antiproton yield due to a reduction in focusing strength. The goal is to develop a lens design capable of 1000 T/m over a 1 cm radius aperture without failing in less than 10E6 pulses [1]. For this, a thorough understanding of the lens electro-mechanical behavior is desired.

The Li cylinder is enclosed in a water-cooled titanium alloy (6Al-4V ELI) jacket called the septum. Its purpose is to contain the Li against the extreme thermal and magnetic loads from the beam and pulse. For proper lens operation, a negative Li hydrostatic stress (preload) of about 2,500psi is required for optimum lens life. This preload is aimed to minimize Li-titanium separation caused by magnetic forces during each pulse.

Mechanical failure of the lens typically occurs in the titanium septum, and although failure theories abound, definitive evidence of a single cause has yet to be identified. A comprehensive finite element model of the lens has been developed using ANSYS® [2,3]. The aim is to better understand the mechanisms leading to failure. One of the main unknowns has been the mechanical behavior of Li at high strain rates. While thermal and electrical properties for Li are well documented, very little mechanical data is available [4]. Basic properties such as modulus of elasticity and plastic behavior have not yet been clearly defined.

TENSILE TESTS

Dog bone shaped tensile specimens were cast as shown in Fig. 1. Tensile tests were conducted on an MTS 880 servo-hydraulic Material Test System. To minimize interaction with the environment, the samples were immersed in mineral oil inside a cylindrical chamber. The chamber was wrapped with heating tape to heat the oil to the required temperature. The oil was fully stirred before testing to ensure a uniform temperature distribution. To prevent the soft sample from bending or twisting during sample insertion, the upper end of the sample was pinned to the testing machine with a specially designed connecting fixture. Stress-strain curves were obtained by recording the load versus displacement data, calibrated using an extensometer during testing. For small strain measurements, strain gauges were attached to the Li sample using a non-reactive adhesive.

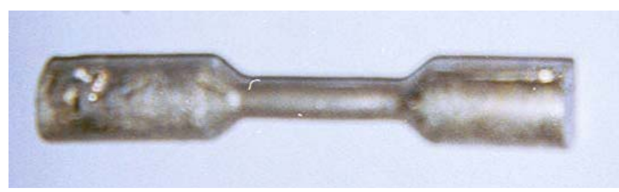

Figure 1: Li tensile specimen.

The samples were pulled at four strain rates ($0.002s^{-1}$, $0.01s^{-1}$, $0.10s^{-1}$, and $1.05s^{-1}$) and three temperatures (room temperature, 50°C, and 75°C). Room temperature plots of true stress versus true strain (σ_T -ε_T) at different strain rates are given in Fig. 2. The modulus of elasticity (E) was calculated from the elastic unloading part of the stress-strain curve ($\sigma_T = E\, \varepsilon_T$). The plastic strain-hardening region can be defined by the equation:

$$\sigma_T = K\varepsilon_T^{\ n} \quad (1)$$

where K and n are hardening parameters. Table 1 lists these parameters together with E values for the different strain rates and temperatures. The yield strength $\sigma_{0.2}$ was defined as the stress at 0.2% strain offset, and the ultimate tensile strength σ_{UTS} was the greatest load the sample withstood before necking and ultimate fracture.

A rate dependent viscoplastic model can be evaluated which accurately describes the hardening behavior. The Perzyna model [5] was employed which is of the form:

$$\sigma_y = \sigma_o \left[1 + \left(\frac{\dot{\varepsilon}}{\gamma^*} \right)^{1/\delta} \right] \quad (2)$$

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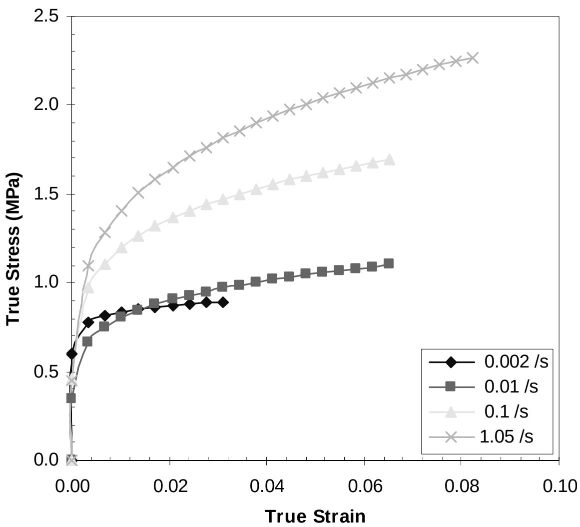

Figure 2: True stress vs. true strain for Li at room temperature and different strain rates.

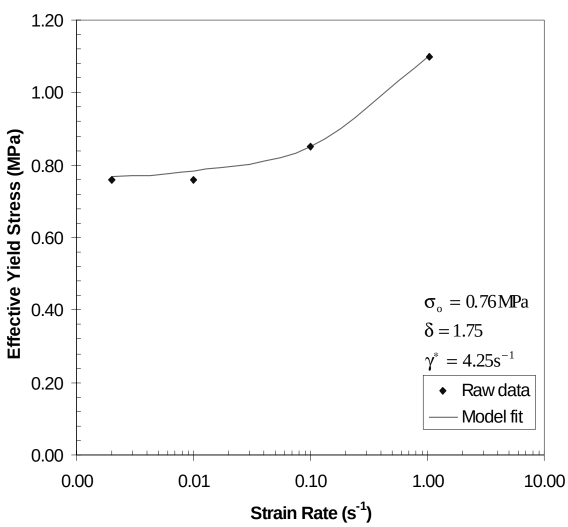

Figure 3: Effect of strain rate on the yield stress of Li at room temperature showing Perzyna model fit.

Table 1: Tensile test results.

Strain Rate /s	0.002	0.01	0.10	1.05
$\sigma_{0.2}$ (MPa)	0.76	0.76	0.85	1.10
σ_{UTS} (MPa)	0.89	1.10	1.69	2.28
n	0.065	0.17	0.19	0.23
K (MPa)	1.12	1.75	2.85	4.03
E (GPa)	7.80	**Room**	**Temperature**	
$\sigma_{0.2}$ (MPa)	0.42	0.50	0.85	0.92
σ_{UTS} (MPa)	0.51	0.76	1.38	1.75
n	0.069	0.14	0.14	0.20
K (MPa)	0.65	1.16	2.14	3.01
E (GPa)	5.00		**50°C**	
$\sigma_{0.2}$ (MPa)	0.41	0.45	0.72	0.90
σ_{UTS} (MPa)	0.46	0.60	1.02	1.54
n	0.053	0.098	0.16	0.19
K (MPa)	0.57	0.81	1.64	2.66
E (GPa)	4.00		**75°C**	

where σ_y is the effective yield stress, σ_o is the static yield stress (σ_{02} at .002s^{-1}), $\dot{\varepsilon}$ is strain rate, $\gamma*$ is the material viscosity parameter, and δ is the strain rate hardening parameter. Fig. 3 shows a plot of effective yield stress vs. strain rate at room temperature and the corresponding Perzyna parameters. The effective yield stress rises sharply beyond strain rates of 0.01.

COMPRESSIVE CREEP TESTS

To simulate the behavior of Li in the septum, a test was conducted to study the dynamic response of Li under compression. A titanium alloy tube with similar dimensions to the septum was filled with Li and pressurized at one end while the other end was capped. The resulting pressure distribution in the Li was measured with respect to time using strain gauges mounted on the exterior of the tube as shown in Fig. 4. Six strain gages spaced at varying intervals were used.

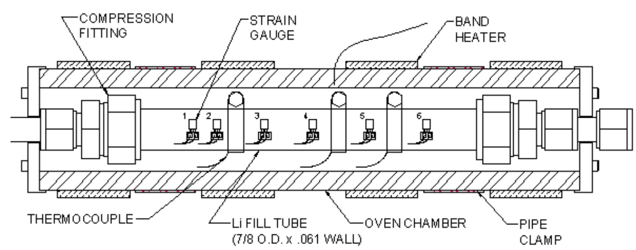

Figure 4: Li fill tube assembly showing (6) strain gauges positioned at 0”, ½”, 1 ½”, 2 ½”, 3 11/16”, and 4 7/8”.

The entire assembly was placed inside a cylindrical oven chamber to heat the Li to the required temperature. Thermocouples mounted on the fill tube monitored the Li temperature. Pressure was applied via a hydraulic system using standard hydraulic oil directly in contact with the Li. Point of load application was close to strain gauge location 1 (SG1). The strain gauge readings were converted to radial stress (preload) values on the tube inner wall (i.e. pressure exerted by the Li on the titanium tube). Tests were conducted at two pressures (2000psi and 4000psi) and four temperatures (room temperature, 50°C, 80°C, and 110°C). Note that the melting point of Li is relatively low at 180.6°C. Results were obtained in the form of preload versus time curves for each strain gage location as shown in Fig.’s 5 and 6.

Creep is a rate dependent material nonlinearity in which the material continues to deform under an applied load, typically accelerated by temperature. From a material viewpoint, creep and viscoplasticity are the same except that the time scales involved are different. Creep, unlike plasticity and Perzyna viscoplasticity, does not involve a yield surface at which inelastic strains occur. Thus, creep strains are assumed to develop at all non-zero deviatoric stresses. Creep strain is typically a function of stress, strain, time, and temperature [6]. Over several pulses in the lens, creep is thought to play an important role as the Li undergoes various loading cycles [2]. Since Li bonds tightly to the titanium surface, a no slip boundary condition is assumed and in the case of the tube test, the time dependent distribution of pressure across the tube is thought to be primarily by creep.

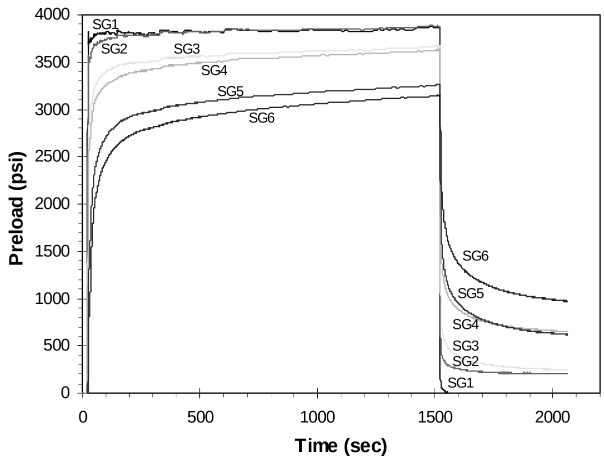

Figure 5: Preload vs. time for Li at 50^{o}C showing relaxation after load removal (4000psi test).

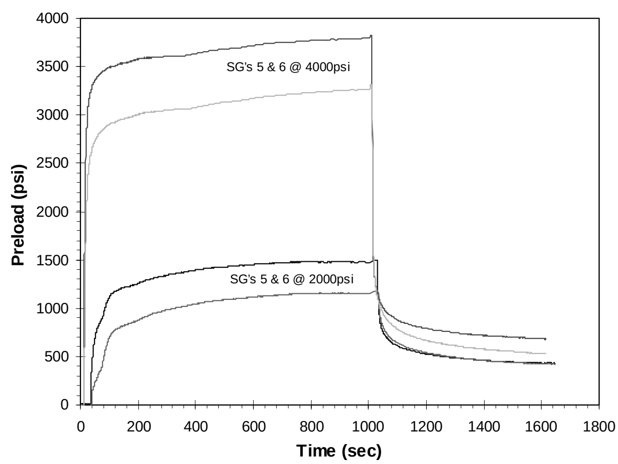

Figure 6: Effect of applied pressure on preload at strain gauge locations 5 and 6 at 80^{o}C.

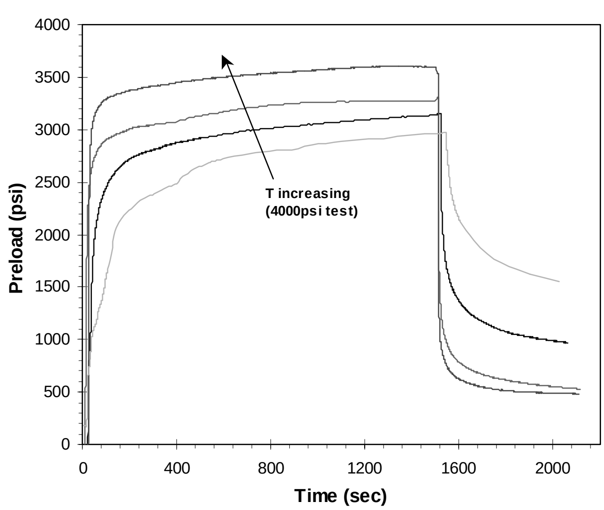

Figure 7: Effect of temperature on preload at strain gauge location 6 (4000psi test).

CONCLUSION

Temperature dependent elastic and viscoplastic properties of Li have been accurately measured in tension. The elastic modulus at room temperature (7.8GPa) was found to be significantly higher than previously published results (2.0-5.0GPa). Li exhibited significant work hardening at higher strain rates with a very small elastic region. The sample stretched considerably with extreme necking before final fracture at a very small cross section.

The compressive creep tests also revealed interesting results. It was seen that Li creeps rapidly especially at higher temperatures as shown in Fig. 7. At lower temperatures, a uniform preload was not achieved across the tube. A drawback of this test was that it did not measure Li creep strain directly. The authors would also like to point out that at the time of writing this paper, data from these tests was still being analyzed and only partial results have been presented. Interested parties should contact the author(s) directly for further information.

Based on the above observations, Li in the lens will most likely undergo some combination of viscoplasticity and creep which will have to be incorporated in the ANSYS® finite element model.

FUTURE WORK

Since Li is almost always in compression in the lens, the tensile tests should be repeated in compression to check for possible differences in material behavior. Higher strain rate tests should also be conducted to see whether Li exhibits further work hardening characteristics, since strain rates in the order of 10^1 and 10^2 are seen in the lens based on finite element analysis [2]. Standard compressive creep tests should also be conducted in which creep strain is measured directly. A temperature dependent comprehensive creep model should be developed from these tests and verified using the tube test results.

REFERENCES

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