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ABSTRACT

Creep behavior of Type 304 LN plate and 316 L shielded-metal-arc (SMA)-deposited stainless weld metal was investigated at 4 K. Testing was performed at constant load in a creep machine with a cryostat designed for long-term stability. Both transient and steady-state creep were observed during tests lasting over 200 hours. Steady-state creep rates were much greater than expected from extrapolations of 300-K creep data. Creep rates on the order of 10^{-10} s^{-1} were observed at stresses around the yield stress for both materials. The stress exponent under these conditions is $\sim$2.3. Possible creep mechanisms at this temperature and the impact of these results on the design of engineering structures for long-term structural stability at cryogenic temperatures are discussed.

INTRODUCTION

Lawrence Livermore National Laboratory (LLNL) is the site for the Mirror Fusion Test Facility (MFTF-B), a tandem-mirror fusion experiment that depends on high-field superconducting magnets for plasma containment. Magnet cases are made from Type 304 LN stainless-steel plate that is joined with Type 316 L stainless-steel filler metal. The magnet cases are at 4 K during operation.

The design lifetime of the MFTF-B is 10^3 full-power cycles over ten years. Design stresses are 67% of the 4-K 0.2% yield strength (σ_y) of the material. Time-dependent deformation that produces plastic strains above 0.2% during MFTF-B's lifetime might cause difficulties.

Time-dependent plastic deformation, or creep, is thought to be an elevated-temperature problem, becoming a factor at temperatures greater than 0.4 T_m, where T_m is the melting temperature of the material in K. Extrapolating elevated temperature steady-state creep rates to cryogenic temperatures, using the activation energy determined at elevated temperatures, yields the conclusion that creep is a negligible

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factor in design at 4 K. Recent studies of long-term creep of copper and its alloys[1] show that creep occurs at temperatures as low as 4 K, and is classical in its behavior and time evolution. Thus, the activation energy must decrease for creep to occur at cryogenic temperatures, which has been confirmed for copper and its alloys.

Primary and steady-state creep are observed at 77 K for copper and its alloys, and both increase with increasing stress. The steady-state creep rates are small ($\sim 10^{-10}$ s^{-1}), but are orders of magnitude greater than predicted by extrapolation of high-temperature data to 77 K. The activation energy measured for steady-state creep of copper at 77 K is about 0.02 eV. The activation energy for steady-state creep of copper by self-diffusion at elevated temperatures is 2.0 eV. Activation-energy changes indicate mechanism changes for creep, so creep at cryogenic temperatures cannot be predicted by extrapolation from higher temperature creep data. Creep rates similar to those measured at cryogenic temperatures could pose an operational problem for some structures. Tien *et al.*[2] reviewed published cryogenic creep data and described creep behavior by alloy system. Besides copper, austenitic stainless steels creep at cryogenic temperatures as low as 20 K for tests up to 100 hours.[3] Recent stress relaxation experiments on Types 304 L and 304 LN stainless steels at 4 K show that failure occurred when stresses in the range of 1100 to 1300 MPa relaxed under locked crosshead conditions, due to time-dependent plastic deformation.[4]

To evaluate the creep resistance of the structural materials used in MFTF-B magnet cases at cryogenic temperatures, the nature and extent of creep observed in these materials must be known. This report summarizes the results of creep tests performed on Type 304 LN plate and Type 316 L weld metal. The objective of this program was to evaluate whether creep is a significant design factor for magnet-case structural materials at 4 K.

TEST PROGRAM

Eight creep tests were run, four each on the plate and weld metal. Tests were planned for 200 hours duration at 4 K. Threaded-end tensile-type creep test specimens with a 31.8-mm length and a 6.4-mm gage diameter were made from materials used in the MFTF-B magnet system. Specimens were mounted in the creep load train in K-Monel grips.

Weld specimens were taken from a shielded-metal-arc (SMA)-deposited (No. 82) weld joint in 75-mm-thick Type 304 LN plate that was welded in the horizontal position, using 3.2-mm-diameter Type E316L-15 electrodes. No postweld heat treatment was used. Radiography and metallographic examination of the weld revealed a few microfissures. The composition of the test materials in weight percent is given in Table 1.

Magne-gage measurements on the weld showed less than 0.5 FN (ferrite number). Longitudinal (L) specimens were taken near the top of the

Table 1. Composition of the Materials Tested in This Program (Weight Percent).

Alloy	C	Mn	P	S	Si	Cr	Ni	Mo	N_2
304 LN	0.03	1.7	0.015	0.015	0.35	19.0	9.0	---	0.15 (nominal)
316 L	0.042	2.6	0.024	0.009	0.35	17.69	13.58	2.22	0.025

weld. Long transverse specimens were taken from near-top, mid-thickness, and near-bottom locations and are designated TL, TM, and TB, respectively. Specimen gage lengths were all weld material.

Longitudinal (L) and long transverse (T) specimens were taken at midthickness from 19-mm-thick Type 304 LN plate. Weld specimens are designated "W82," whereas the Type 304 LN plate and specimens are designated by a "BM" identifier.

Weld metal and base metal 4-K tensile properties are presented in Table 2. Tensile properties of Type 304 LN were higher than expected.

TEST METHODS

Testing was done using methods described in Ref. 5. A schematic diagram of the facility is shown in Fig. 1.

Dead-load creep tests were performed using a 20:1 load-magnification lever arm in a top-loading Janus 10DT vacuum-walled cryostat with a LHe capacity of 7 litres, and fitted with a tensile testing insert. The specimen chamber was purged, precooled, and then flooded with LHe. The system was allowed to thermally equilibrate at 4 K for 24 hours prior to loading. The nitrogen jacket surrounding the LHe chamber is automatically refilled on a 27-minute schedule to maintain thermal stability of the pull-rod assembly. The LHe level in the specimen chamber was maintained above the top of the upper grip.

Temperature was measured with teflon-sheaved copper-constantan thermocouples on the upper and lower grips. A LHe reference junction was used. During testing, no temperature gradient was observed across the specimen. Temperature measurements are accurate to 1 K.

Creep strain was measured using two noncontacting capacitance displacement gages mounted 180° apart on the test specimen. The gages are model 2500 capacitance strain-gage system, made by Mechanical Testing Instrument Company (MTI), and were mounted on the upper grip. Polished targets for the gages were mounted on the lower shank of the specimen. Gage displacement was calibrated in LHe and 300-K air. This gage system has a linear range of 1.25 mm and a resolution of 0.127 µm in air. Differences in displacement gages on loading indicated that specimens were subject to bending. This condition was detected and avoided.

Table 2. Tensile Properties of Type 304 LN Plate and Type 316 L Weld Metal at 4 K.

Specimen	0.2% Yield Stress (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Reduction in Area, RA (%)	Modulus of Elasticity (GPa)
82-L	672	1200	53.8	43.7	138
82-TL	635	1104	36.2	21.7	229.1
82-TM	634	1096	21.6	20.9	216.7
82-TB	667	1446	38.6	37.9	199.4
BM-L	827	1599	31.7	---	---
BM-T	949	1838	43.8	---	---

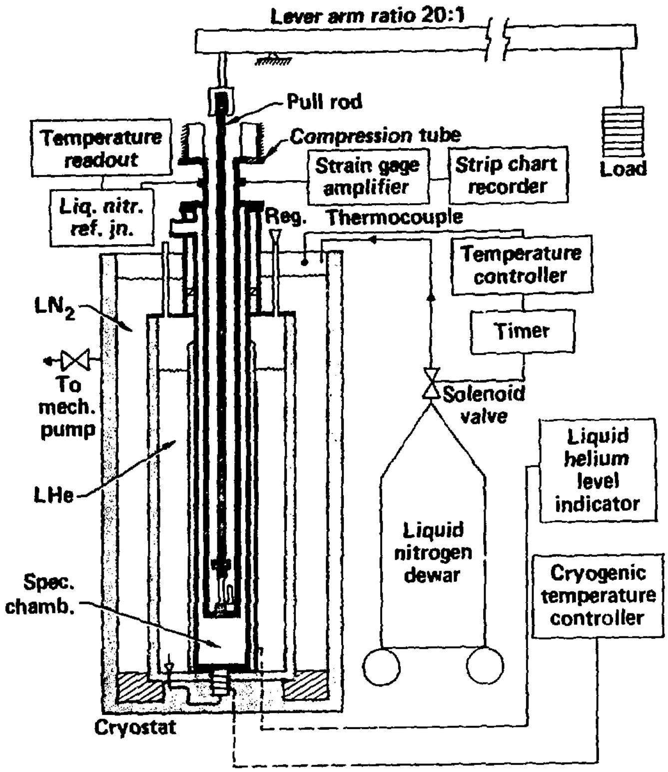

Figure 1. Facility for creep testing at cryogenic temperatures.

Creep strain is calculated from the averaged reading of the two gages. Tests were performed on three stress levels: (1) the nominal design stress, e.g., 67% of 4-K σ_y; (2) σ_y; and (3) 120% of σ_y.

Strain-versus-time plots for Type 304 LN are in Fig. 2. Test BML2 showed much more strain accumulation than the other three tests. A broken helium gas-pressure release valve caused persistent temperature-control problems until 112 hours into this test. Temperature excursions to 50 K were observed. After 112 hours, the test proceeded smoothly.

Significant primary and steady-state creep, which are a function of stress and material strength, were seen for all Type 304 LN specimens (see Table 3). Primary creep lasted from 2 to 100 hours, producing primary creep strains of 0.01 to 0.05%. Steady-state creep rates up to 1.98×10^{-10} s^{-1} were seen. Applied stresses below 0.5 σ_y resulted in creep below the equipment's resolution. Applied stresses between 0.5 σ_y and σ_y produced enough creep to be considered in design.

The stress dependence of the steady-state creep rate for Type 304 LN tests is shown in Fig. 3. The two specimens tested at 0.67 σ_y and at σ_y yield a plot of steady-state creep rate versus stress with a slope of 2.3. Specimen BML4, which work hardened during loading, showed a lower steady-state creep rate and a smaller amount of primary creep than other Type 304 LN specimens. Suppression of primary creep by prior plastic deformation is well known at elevated temperatures and applies for cryogenic creep of Type 304 LN as well.

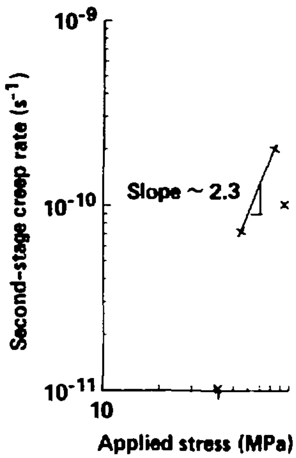

Figure 2. Stress dependence of second-stage creep rate for Type 304 LN plate at 4K.

Table 3. 4-K Creep Results for Types 304 LN Plate and 316 L Weld Metal.

Specimen	Applied Stress, σ (MPa)	$\frac{\sigma}{\sigma_y}$	Strain on Loading ($\times 10^6$)	Strain on Unloading ($\times 10^6$)	Test Time (Hours)
BML1	555	0.67	4880	4710	193.1
BML2	828	1.0	11322	7826	215.6
BML3	414	0.5	5218	4116	216.7
BML5	936	1.13	27250	9034	239.6
W82L2	828	1.2	2800	---	191.5
W82TM2	607	1.0	7436	6140	215.0
W82TL2	425	0.67	5925	4620	142.6
W82TB2	697	1.0	8054	6793	190.5

Specimen	Primary Creep Strain ($\times 10^6$)	Duration of Primary Creep Strain (Hours)	Secondary Creep Amount ($\times 10^6$)	Secondary Creep Rate (s^{-1})	Duration of Secondary Creep (Hours)	Total Creep Strain ($\times 10^6$)
BML1	350	20	46	7.13×10^{-11}	180	396
BML2	500	60	71	1.98×10^{-10}	155	571
BML3	140	2	---	$<1.0 \times 10^{-11}$	---	141
BML4	100	100	31	1.0×10^{-10}	89	132
W82L2	>100	---	50	8.2×10^{-11}	>100	50
W82TM2	450	35	17,800	$0.001 - 1.0 \times 10^{-8}$	160	18,290
W82TL2	< 10	---	< 10	$<1.0 \times 10^{-11}$	---	< 10
W82TB2	20	50	40	8.0×10^{-11}	140	60

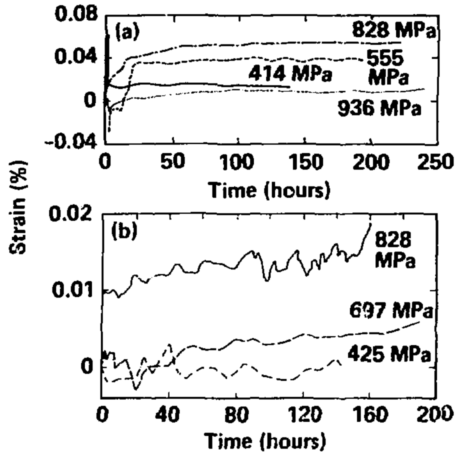

Figure 3. Strain vs time at 4 K for (a) Type 304 LN plate and (b) Type 316 L weld metal.

The creep magnitude, steady-state creep rates, and the value of the stress dependence of steady-state creep are consistent with those observed for copper and copper alloys at 77 K,[1] suggesting that mechanisms for steady-state creep of copper might apply to Type 304 LN. Determination of the activation energy for steady-state creep and activation volume for primary creep is required to verify this hypothesis.

The unrecovered strain due to a temperature excursion was factored out of test BML2. However, its existence raises a question with regard to deformation of magnet cases during a transient warmup condition, should a large part of the loads remain. A strain excursion occurred for weld metal specimen W82TM2. However, no temperature excursions were seen. Weld specimen W82TM2 showed periods with steady-state creep rates as high as 1×10^{-8} s^{-1} between large strain jumps. Total creep strain for test W82TM2 was 1.8% in 200 hours. Severe slip patterns were observed on the surface of the test specimen after unloading, but were not observed on specimen BML2, despite a similar total creep strain indication, supporting the argument that the strain jumps were not real in the case of specimen BML2.

Microcracking, microstructural inhomogenieties such as ferrite at dendrite boundaries, inclusions, slag, and porosity are present in weld 82 and might contribute to the observed strain behavior.

Strain-versus-time data for the other weld metal samples are shown in Fig. 2. The amount of creep and creep rate increases with increasing

Table 4. Estimated Creep Effect for MFTF-B and MARS

Machine	Planned Number of Full-Power Years of Operation	Maximum Stress in Magnet Case	Estimated Strain at End of Life
MFTF-B	$\sim$ 0.0001	462 MPa	0.095%
MARS	24	462 MPa	3.5%

stress. At 0.67 σ_y, creep was below the resolution of the test equipment. Creep rates as high as 8.2×10^{-11} s^{-1} were measured. The weld metal was not affected by loading above σ_y. The amount of creep and its rate were larger than when stressing below σ_y. This test, W82L2, exceeded the range of the capacitance gage and was terminated early. The gage was incorrectly positioned for 5% full range. This was avoided in subsequent tests.

Consider the effect of creep in Type 304 LN plate on the planned operation of two tandem-mirror fusion experiments, MFTF-B and MARS (see Table 4).[6] For the planned operating scenarios, strain accumulation by creep will not be a problem in MFTF-B magnet cases, but will definitely be a problem in a typical power reactor.

CONCLUSIONS

1. Significant primary and steady-state creep is seen for Type 304 LN plate and SMA-deposited Type 316 L weld metal at 4 K. Steady-state creep rates about 1×10^{-10} s^{-1} were measured at applied stresses close to σ_y at 4 K.

2. From an engineering standpoint, accumulation of creep damage in Type 304 LN plate will not be a problem in MFTF-B (0.095% strain), but will be a problem in power-producing fusion plants, such as MARS (3.5% strain).

3. Appreciable creep strains (on the order of 2% plastic strain) and creep rates were observed in Type 316 L weld material in one case. The microstructural features causing the large creep rate are possibly associated with segregation and small cracks (i.e., microfissures) in the weld metal.

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