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CREEP OF Zr-2.5 wt% Nb
ALLOY PRESSURE TUBES

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CREEP OF Zr-2.5 wt% Nb ALLOY PRESSURE TUBES

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June 1969

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P. J. Pankaskie

ABSTRACT

Creep and stress rupture data were obtained from prototypic reactor pressure tubing. Biaxial stress conditions, with a hoop to axial stress ratio of 2 to 1, were maintained by a constant internal pressure. Most of the testing was done at 400 °C on tubing in the heat treated condition. Some tests were done at 300 °C on tubing in the 30% and 60% cold work temper. The data obtained suggests that the heat treated condition is sufficiently stable for use at 400 °C.

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CREEP OF Zr-2.5 wt% Nb ALLOY PRESSURE TUBES

P. J. PANKASKIE

INTRODUCTION

Within the United States, there are several water-cooled thermal reactors using pressure tubes in the primary core section coolant system. In Canada, many power reactors are of the pressure tube type. For these power producing thermal reactors, zirconium alloys are used as pressure tube material because of their low neutron cross sections and because of their strength at intermediate temperatures (e.g. to 400 °C). One of the more promising of the zirconium alloys is the Zr-2.5 wt% Nb alloy. This alloy appears to be amenable to some combination of cold working and heat treatment that may improve strength properties over that obtainable from Zircaloy-2 that has been the pressure tube material generally used. Hence this alloy is being evaluated as a candidate material for pressure tube use in water cooled, thermal reactors now in the planning stages.

The work described herein was done under a USAEC-AECL Cooperative Agreement. One of the objectives of the Cooperative Agreement was to obtain creep and stress rupture data from prototypic pressure tubing. This report presents the creep and stress rupture data obtained up to the conclusion of the USAEC-AECL Cooperative effort.

SUMMARY AND CONCLUSIONS

Creep and stress rupture data was obtained from tubing biaxially stressed by internal pressurization at 300 and 400 °C for test durations to nearly 12,000 hr. At 300 °C, tubing was tested in the 30% cold worked temper. At 400 °C, tubing was tested in two heat treated conditions.

At 400 °C, creep rates and rupture times for heat treated tubing show relatively little scatter, suggesting that the heat treated condition is rather stable under stress for long times at this temperature.

At 300 °C, the average diametral strains along the length of a tubular test specimen tend to be uniform up to nearly 2% total strain. At 400 °C the uniform strain tends to be very much less (about 1/2%) and in some cases may be absent entirely.

At both 300 and 400 °C, local bulging always precedes failure, and the origin of the failure is at the locally bulged area. Failure often results in a longitudinal split which arrests when the internal pressure is relined.

DISCUSSION

TEST MATERIALS AND PROCEDURES

Tubular specimens, nominally 2 in. ID by 0.180 in. wall prototypic pressure tubing, were creep and stress rupture tested in the cold worked and heat treated conditions. Specifically, the material conditions were:

- 30% cold worked temper
- 30% and 60% cold work, solution treat at 880 °C, water quench and age at 500 °C for 24 hr
- Solution treat at 880 °C, water quench, 15% cold work and age at 500 °C for 24 hr.

The 30 and 60% cold worked tubing was produced from magnesium reduced sponge and fabricated by hot extrusion and tube reducing (Rockrite process). The heat treated and 15% cold worked tubing was produced from sodium reduced sponge and fabricated by hot extrusion and cold drawing.

Tubing in the material conditions (e.g. cold work and heat treated) employed in these investigations were also used in

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FIGURE 1. Tube Test Assembly Ready for Pressurizing. (In the foreground is an exploded view of end caps.)

crack propagation investigations.⁽¹⁾ From those tests, ultimate burst strength ranged from about 80 to 90 ksi at 300 °C to about 115 to 125 ksi at room temperature.

The tubular test specimens were nominally 16 in. long to minimize end effects. In some tests the ends of the tube were sealed against leakage of the internal pressurizing fluid by threaded and seal-welded end plugs; in other tests mechanical end fittings were used. The general tube assembly with mechanical end seals and ready for pressurizing is shown in Figure 1.

Tests were run at 300 and 400 °C. At 300 °C, the desired hoop stress was achieved by internally pressurizing with water, maintained in the fluid state throughout the test. At 400 °C, the desired hoop stress was achieved by internal pressurization with helium for the duration of the test. In all tests, the external test specimen atmosphere was stagnant air. Hence, at 400 °C particularly, the test specimen oxidized to a whitish-tan color. On all specimens, the oxide coat remained intact and adherent for the duration of the tests.

The tubular test specimen was cooled and depressurized for each set of creep strain measurements. The tube circumference was measured at the 1/4, 1/2, and 3/4 lengths with a Pi-tape providing an average diameter measurement. Hence, all strains and creep rates reported are average values.

TEST RESULTS

The data obtained from the creep and stress rupture tests are shown graphically in Figure 2. More detailed time-history data are tabulated in Table 1.

The bulk of the creep and stress rupture tests were done at 400 °C and on heat treated material. Only a few tests at 300 °C were done and only on tubing in the cold worked

is fairly uniform up to average strains of about 1/2%. In spite of the lesser uniformity in strain, there appears to be somewhat less scatter in average secondary creep rates about the stress-creep rate curve. The reasons for the decrease in uniform average strain are not obvious but may be due in part to variations in wall thickness throughout the tubular test specimen and to minor temperature variations. If one plots a time-strain curve for each of the three measurements (e.g., 1/4, 1/2, and 3/4 points along tube length) three separate curves, in some cases, will be obtained. When this occurs, one also finds that these curves usually diverge more and more as the test progresses. Failure will ultimately occur in the area that creeps first and fastest.

In Figure 2, rupture times as a function of nominal hoop stress are also plotted. Again the curves at 300 and 400 °C are roughly parallel. Only two data points, however, are available from 300 °C tests. At 300 °C, very high hoop stresses are required to produce stress rupture in less than 10,000 hr. At 400 °C, rupture strength drops appreciably. Even a stress of 15 ksi will produce failure in less than 10,000 hr. With the exception of test HT-3, there is relatively little scatter about the Stress-Rupture Time Curve. At 300 °C, failure follows relatively soon after the average diametral strain is noticeably nonuniform. Failure occurs by very localized bulging and a short split in the tube (see Figure 3). Since at 400 °C average diametral strains may be noticeably nonuniform early in the test and at low strains, the early prediction of failure is difficult. At failure, however, strain is very localized, as was the case with tubing tested at 300 °C. In some instances, actual failure occurs as a "pinhole" leak or a short split in the locally deformed area. At both temperatures the split, when it occurs, is always parallel to the tube axis

condition. Tubing in the 30% CW and 60% CW was not tested at 400 °C because:

- Based on results from creep and stress rupture testing of Zircaloy-2^(2,3) significant amounts of cold work recovery would likely occur at 400 °C but not at 300 °C.
- Based on investigations at Chalk River National Laboratory,⁽⁴⁾ interest was shifting to the heat treated tubing because of strength improvements.

Since heat treatment investigations showed that the heat treated condition was stable at 300 °C,⁽⁴⁾ emphasis was placed on testing at 400 °C to determine whether the heat treated condition was stable and whether higher reactor operating temperatures were possible.

Creep rates at both 300 and 400 °C increase uniformly with increasing stress. With some scatter, the data points lie on straight lines when plotted on a semi-log scale and the 300 and 400 °C curves are approximately parallel. It should be remembered that these data points are average secondary creep rates rather than minimum values. Sufficient strain-time data for establishing minimum secondary creep rates is not easily obtained because of the time and difficulty in interrupting the test for strain measurements. In examining the time-history data in Table 1, note that at 300 °C and at relatively low strains, the average diameter increase within any one tubular test specimen is fairly uniform. For the cold worked tubing it appears that the average diametral strain along the length of a test specimen is fairly uniform at average strains to nearly 2%. Minimum creep rates occur at less than about 1% average diametral strain. At 400 °C, the magnitude of the average uniform strain is substantially less. In some cases the average diametral strain along the length of the tubular test specimen is nonuniform from very early in the test, while in others it

TABLE 1. (contd)

Test Identity	Hoop Stress, ksi	Test Temperature, °C	Rupture Time, hr	Approx Min Creep Rate, %/hr	Time, hr	Circumferential Strain			Failure Mode
						$C_1, \%$	$C_2, \%$	$C_3, \%$	
HT-4A	15	400	6,566	1×10^{-4}	94	0.21	0.12	0.12	Pinhole leak at bulge.
					260	0.21	0.21	0.21	
					746	0.42	0.54	0.58	
					1,274	0.54	0.84	0.92	
					1,722	0.67	0.88	1.21	
					3,992	2.00	2.96	4.35	
					5,194	2.70	5.80	8.50	
					5,720	2.80	6.05	10.0	
					6,566	2.85	7.5	27.	
HT-24A	55	300	2,369	1×10^{-3}	120	0.59	0.59	0.63	Bulge and longitudinal split.
					360	0.71	0.67	0.71	
					1,340	1.63	1.76	1.84	

TABLE 1. (contd)

Test Identity	Hoop Stress, ksi	Test Temperature, °C	Rupture Time, hr	Approx Min Creep Rate, %/hr	Time, hr	Circumferential Strain			Failure Mode
						$C_1, \%$	$C_2, \%$	$C_3, \%$	
HT-2	50	300	Discontinued at 1,589	--	93	0.03	0.08	0.08	Pinhole at bulge.
					764	0.04	0.08	0.09	
					911	0.16	0.12	0.29	
					1,589	0.21	0.13	0.29	
					98	0.04	0.04	0.04	
	25	400	1,473	5×10^{-4}	332	0.25	0.29	0.40	
					499	0.38	0.50	0.83	
					858	0.58	0.95	1.56	
					1,194	1.0	1.75	3.45	
HT-3	20	400	9,035	3×10^{-4}	68	0.14	0.04	0.08	Pinhole at bulge.
					162	0.12	0.12	0.16	
					424	0.20	0.20	0.25	
					1,776	0.20	0.50	0.50	
					3,372	0.66	0.91	1.07	
					4,548	0.66	1.44	1.57	
					5,194	0.75	1.65	2.40	
					5,770	0.75	1.77	2.70	
					7,080	0.83	2.10	3.59	
					8,078	0.83	2.39	4.75	
HT-7	16.5	400	7,250	2×10^{-4}	9,035	0.95	2.68	15.2	Bulge and short longitudinal split.
					114	0	0	0.12	
					733	0.33	0.33	0.37	
					1,462	0.71	0.92	0.83	
					2,778	1.04	1.41	1.54	
					4,022	1.66	2.70	3.50	
					4,355	2.13	2.48	3.80	
					27	6.9	6.5	7.2	
HT-1A	40	400	27	--					Bulge and longitudinal split.
HT-2A	30	400	295	2×10^{-3}	139	2.1	3.2	3.2	Bulge and longitudinal split.
					284	3.5	8.6	8.1	longitudinal split.
HT-3A	25	400	742	3×10^{-4}	138	0.41	0.65	0.65	Bulge and longitudinal split.
					280	0.67	1.12	1.21	longitudinal split.
					446	0.97	1.92	2.23	longitudinal split.

TABLE 1. Creep and Stress Rupture Test Results

Test Identity	Hoop Stress, ksi	Test Temperature, °C	Rupture Time, hr	Approx Min Creep Rate, %/hr	Time, hr	Circumferential Strain			Failure Mode
						C ₁ , %	C ₂ , %	C ₃ , %	
30-2-SR	61	300	1,453	8×10^{-4}	26	0.59	0.59	0.59	Localized bulging followed by a short longitudinal split.
					71	0.80	0.80	0.80	
					235	1.22	1.22	1.22	
					670	1.77	1.88	1.88	
					993	2.10	2.35	2.40	
30-11-Sr	50	300	Discontinued at ~12,000	4.6×10^{-4}	24	0.41	0.41	0.41	
					93	0.54	0.54	0.54	
					254	0.67	0.67	0.67	
					544	0.84	0.84	0.84	
					1,210	0.92	0.92	0.92	
					1,863	1.01	1.01	1.01	
					3,589	1.47	1.47	1.47	
					5,814	1.56	1.56	1.56	
					8,234	1.76	1.76	1.76	
					9,310	1.93	1.93	1.93	
					11,187	1.94	1.94	1.94	
					11,984	1.95	1.95	1.95	
30-3-SR	36	300	Discontinued at 10,725	5×10^{-6}	2,086	0.96	0.96	0.88	No Failure
					3,212	1.00	1.08	1.13	
					4,070	1.00	1.13	1.13	
					4,166	1.13	1.13	1.17	
					4,977	1.17	1.21	1.17	
					5,613	1.21	1.25	1.29	
					6,029	1.21	1.25	1.29	
					7,709	1.21	1.25	1.29	
					10,749	1.25	1.29	1.34	
					188	1.66	2.11	2.56	Local bulge and short longitudinal split.
	25	400	660	5×10^{-3}	354	2.48	3.73	4.79	
					492	2.98	4.60	6.6	
HT-1	30	400	317	1×10^{-3}	24	0	0	0.12	Local bulge and short longitudinal split.
					72	0.36	0.71	0.96	
					166	0.71	1.50	2.75	
					256	1.12	3.58	10.1	

FIGURE 2. Creep Rate and Rupture Time Versus Stress for Zr-2.5 wt% Nb Alloy Pressure Tubing

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FIGURE 3. Zr-2.5 wt% Nb Tube Specimen After Failure in Stress Rupture Tests. Upper tube was tested at 400 °C and the failure was a pinhole in the locally bulged area. Note the whitish/tan oxide surface. The lower tube was tested at 300 °C and failure occurred by a split initiated in the locally bulged area.

and follows the maximum shear plane through the tube wall. At both 300 and 400 °C the split tends to be arrested when the internal pressure is relieved.

There is insufficient data to compare the cold worked condition with the heat treated conditions. At 400 °C the creep and stress rupture behavior of tubing in both heat treated conditions are quite similar. The addition of the 15% cold reduction between the quench and aging appears to have little or no effect at 400 °C. At 400 °C, there is no large amount of scatter (excepting test HT-3) in either rupture time or creep rate. This lack of scatter suggests that the heat treated state is rather stable under stress for relatively long times.

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