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HIGH-TEMPERATURE FATIGUE BEHAVIOR OF UNIRRADIATED V-15Cr-5Ti TESTED IN VACUUM*

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Limited results of in-vacuum fatigue tests are presented for unirradiated V-15Cr-5Ti tested at room temperature, 550, and 650°C, respectively. The test data were analyzed using a power law equation to correlate the total strain range and cycles to failure. Comparison with data for 20% cold-worked type 316 stainless steel tested at 550°C shows that on the basis of strain range the vanadium alloy is about the same as the stainless steel below 10,000 cycles to failure but becomes superior above the point. The general data trend further suggests that endurance limits may exist at strain ranges of approximately 0.7 and 0.6% at 550 and 650°C, respectively.

1. INTRODUCTION

For some fusion reactors which operate in a cyclic mode, thermal cyclic fatigue and crack growth may limit the service life of the first wall components. Refractory metal alloys would reduce these limitations because of high temperature strength, good thermal conductivity, compatibility with liquid metal coolants, and apparent resistance to radiation damage.(1) The thermal stress resistance (which is a function of thermal conductivity, the thermal expansion coefficient, Poisson's ratio, the modulus of elasticity, and the yield strength) of refractory metal alloys is generally several times better than that of stainless steel.(2) This would allow a higher operating temperature and th[illegible] re would take advantage of increased therm[illegible] o[illegible] ersion efficiency or higher wall load[illegible] Offsetting these advantages are high costs, the lack of production capacity, environmental effects, and a limited data base.

The tensile and creep properties of vanadium and vanadium base al[illegible]s have been studied extensively in suppor[illegible] of previous programs on vanadium cladding development for bre[illegible] reactor fuel elements and high temper[illegible] alloys for space power systems. In c[illegible]ast to the abundance of such data, there is a near total lack of information on the fatigue properties, which are relevant and critical to the design of a fusion first wall. The purpose of this paper is to present baseline information on fatigue properties of unirradiated V-15Cr-5Ti subjected to fully reversed strain-controlled cyclic loading. Since the ongoing test program is still in progress, only limited results obtained to date are reported here for in-vacuum fatigue tests on this alloy at room temperature, 550, and 650°C, respectively.

2. SPECIMENS AND EXPERIMENTAL DETAILS

Specimen stock of V-15Cr-5Ti was obtained in the form of 6.4-mm-diam rods (Heat No. CAM-835-83) in a cold-worked (80-90% cold deformation) condition. The chemical composition (wt %) of the finished rods was 6.2Ti, 14.5Cr, 0.032C, 0.031O, and 0.046N, with the balance V.

The fatigue specimen used in this experiment is shown in Fig. 1. It is a miniature hourglass specimen which has a gage diameter of 3.18 mm with a 12.7-mm fillet radius. Before machining of the specimens, the bar stock was annealed at 1200°C in a vacuum below $10^{-?}$ Pa. Results of this heat treatment were examined by optical metallography and hardness measurements. Photomicrographs of as-received and heat-treated samples are shown in Figs. 2a and 2b, respectively. Examinations indicate that the desired grain size of approximately 30 μm was attained. Full recrystallization and no visible microcracks were seen subsequent to the heat treatment. The average values of five Vickers Diamond Pyramid Hardness (DPH) tests performed on the end cross section were 285 in as-received and 213 in annealed condition. The high hardness value resulted from the cold work. Specimens were stress relieved after machining at 1200°C for 0.5 h in vacuum.

Tests were performed on a closed-loop servo-controlled electrohydraulic fatigue tester equipped with a high vacuum chamber capable of pressures below 10^{-} Pa. Specimens were

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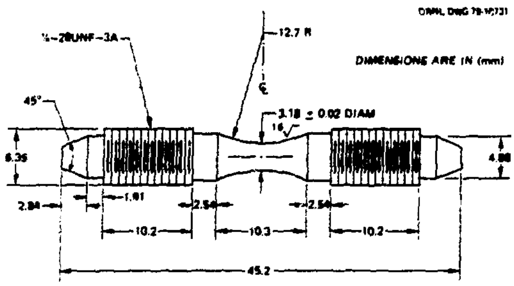

Figure 1 : Hourglass fatigue specimen

heated by an induction generator, maintaining the test temperature within ±2°C during the test. A diametral extensometer designed specifically for applications in a high vacuum environment and at high temperatures was used. However, loading was controlled by axial strain calculated from the measured diametral strain via a strain computer. A fully reversed triangular wave function beginning with compression was used at a strain rate of 0.004/s for all low cycle testing under strain control. High cycle testing was conducted initially in strain control but switched to load control after stable, essentially elastic cycling was established. At that time the strain rate was increased to 0.04/s.

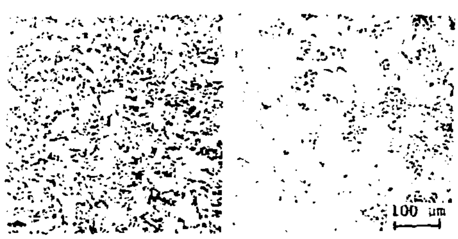

Figure 2 : Photomicrographs of V-15Cr-5Ti in (a) as-received condition and (b) annealed 1 h at 1200°C in vacuum

3. RESULTS AND DISCUSSION

Test data obtained to date from ongoing in-vacuum fatigue tests are shown in Fig. 3, and detailed test results are summarized in Table 1. A room temperature test (AV-52) conducted at a strain range of 0.6% was discontinued after 2×10^5 cycles, as indicated with an arrow directed toward the right of the data point shown in Fig. 3; apparently, this strain range was below the endurance limit at this temperature. The remaining room temperature data indicate that a power law relationship between the total strain range and cycles to failure is appropriate. The following equation was used in the analysis of the room temperature data:

$$\Delta\varepsilon_t = AN_f^{-\alpha} + BN_f^{-\beta} \quad (1)$$

where

$\Delta\varepsilon_t$ = total strain range in %,

N_f = number of cycles to failure, and

A, B, α, and β = material constants.

The values of the material constants are tabulated in Table 2. Similar relations, compensated for temperature effects, were postulated for the elevated temperature data aided by the somewhat incomplete results of three elevated temperature tests, one at 650°C (AV-57) and two at 550°C (AV-514 and AV-511), indicated with arrows as shown in Fig. 3. These tests were ended with fractures that occurred outside the gage section. The reasons for this abnormal failure mode are still unclear, but it appears that the alloy may be somewhat sensitive to the presence of stress risers when cycled in the high cycle range at elevated temperatures.

When V-15Cr-5Ti was subjected to fully reversed strain-controlled cyclic loading, the stress range of the hysteresis loops increased as the test proceeded, a behavior called cyclic hardening. Figure 4 shows the peak-to-peak amplitudes as a function of number of

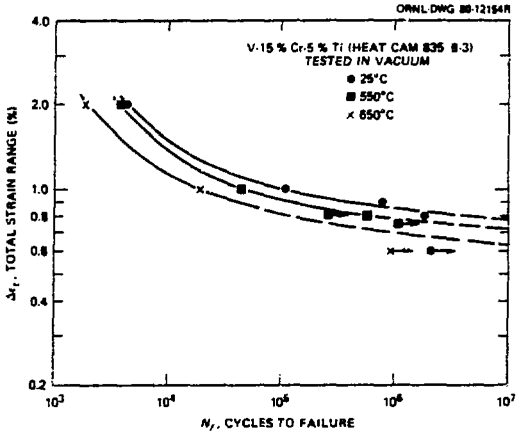

Figure 3 : Cyclic fatigue data for V-15Cr-5Ti tested at 25, 550, and 650°C in vacuum

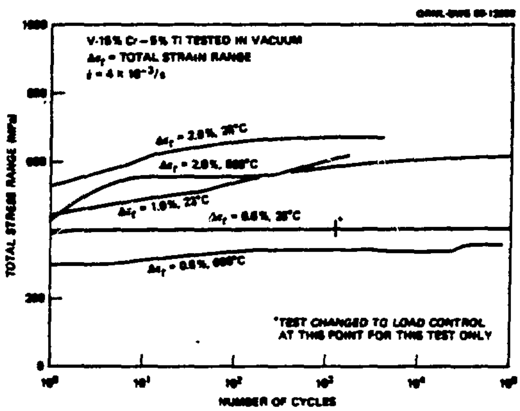

Figure 4 : Cyclic stress behavior of V-15Cr-5Ti tested at 25 and 650°C

cycles. All tests at room temperature exhibited monotonic cyclic hardening, whereas at 650°C some stress range stability was noted after 10-200 initial cycles. Cyclic hardening resumed at the end of the stress range stability in tests of 650°C.

A behavior called elastic stress shakedown was observed in tests cycled to 0.6% strain range, apparently resulting from monotonic cyclic hardening. At 650°C the alloy showed a complete shakedown with saturation after about 200 cycles. Subsequently, the alloy behaved practically as an elastic solid, provided that the maximum cyclic strain range, previously attained, was not exceeded.

The vanadium alloy data were compared to recently obtained in-vacuum fatigue data(3) on 20% cold-worked type 316 stainless steel tested at 550°C, as shown in Fig. 5. The vanadium alloy data fell within the scatter band of stainless steel data in the low cycle range (life below 10^4 cycles). However, at strain ranges below about 0.8% the vanadium alloy exhibited superior fatigue behavior in comparison to the stainless steel, which showed an apparent endurance limit at 0.35% strain range. The endurance limit strain range for V-15Cr-5Ti tested at 550°C appears to be about a factor of 2 greater than this value. A lower endurance limit at a strain range of approximately 0.6% would be expected at 650°C.

4. CONCLUSIONS

1. Results obtained from in-vacuum fatigue tests on V-15Cr-5Ti show that a power law relation between the total strain range and cycles to failure is appropriate.
2. Annealed V-15Cr-5Ti tested at 650°C showed cyclic hardening with saturation after about 10-200 cycles. The alloy also showed a complete elastic stress shakedown when tests were cycled to 0.6% strain range.
3. Beyond approximately 10^4 cycles to failure, the alloy at 550°C shows better fatigue resistance than 20% cold-worked type 316 stainless steel tested in the same manner.
4. The general data trend suggests that endurance limits may exist at strain ranges of approximately 0.7 and 0.6% at 550 and 650°C, respectively.
5. On the basis of existing data and extrapolation, it appears that this alloy has potential value for fusion reactor applications.

Investigations at high temperatures in the strain ranges below 0.9% are continuing. Therefore, no conclusion will be made until more data become available for further evaluation.

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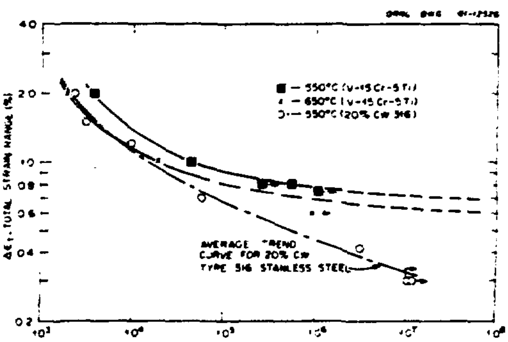

Figure 5 : Comparison of fatigue behavior of 20% cold-worked type 316 stainless steel tested at 550°C with V-15Cr-5Ti tested at 550 and 650°C, respectively

Table 1. Results of fatigue tests on unirradiated V-15Cr-Ti

Specimen[a]	Test Temperature (C°)	Total Strain Range (%)	Maximum Total Cyclic Stress Range, $\Delta\sigma$ (MPa)	Cycles to Failure	Mode of Test Control[b]	Comments
AV-53	27	2.00	1340	4,345	SC	
AV-51	27	1.00	1200	109,125	SC	
AV-515	23	0.90	1074	781,200	SC/LC	
AV-520	20	0.80	922	1,860,000	SC/LC	
AV-52	27	0.60	830	>2,047,020	SC/LC	*c*
AV-510	550	2.00	1240	3,783	SC	
AV-58	550	1.00	1080	43,555	SC	
AV-521	550	0.80	952	595,200	SC/LC	
AV-514	550	0.80	964	>260,220	SC/LC	*d*
AV-511	550	0.75	920	>1,072,410	SC/LC	*d*
AV-54	650	2.00	1228	1,874	SC	
AV-56	650	1.00	1080	19,452	SC	
AV-57	650	0.60	717	>951,302	SC/LC	*d*

[a]All specimens were annealed 1 h at 1200°C in vacuum.

[b]SC = strain control with $\dot{\varepsilon}_t = 4 \times 10^{-3}$/s; SC/LC = strain control transferred to load control with $\dot{\varepsilon}_t = 4 \times 10^{-2}$/s when the response becomes elastic.

[c]Specimen did not fail; test discontinued.

[d]Specimens ruptured outside the gage section.

Table 2. Material constants for equation (1)

Temperature (°C)	A	α	B	β
25	1.67	0.048	6208	1.055
550	1.54	0.048	1432	0.887
650	1.66	0.061	1170	0.948