FATIGUE BEHAVIOR OF UNIRRADIATED V-5Cr-5Ti – B. G. Gieseke, C. O. Stevens and M. L. Grossbeck (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this research is to determine the low cycle fatigue behavior of V-5Cr-5Ti alloys for a range of temperatures and the extent of environmental effects at ambient temperatures.

SUMMARY

The results of in-vacuum low cycle fatigue tests are presented for unirradiated V-5Cr-5Ti tested at room temperature (25), 250, and 400°C. A comparison of the fatigue data generated in rough and high vacuums shows that a pronounced environmental degradation of the fatigue properties exists in this alloy at room temperature. Fatigue life was reduced by as much as 84%. Cyclic stress range data and SEM observations suggest that this reduction is due to a combination of increases in rates of crack initiation and subsequent growth. The relative contribution of each difference is dependent upon the strain range.

In high vacuum, the fatigue results also show a trend of increasing cyclic life with increasing temperature between 25 and 400°C. From the limited data available, life at 250°C averages 1.7 times that at 25°C, and at 400°C, life averages 3.2 times that at room temperature. Like the environmental effects at 25°C, the effect of temperature seems to be a function of strain range at each temperature.

The total strain range and cycles to failure were correlated using a power law relationship and compared to 20% cold-worked 316 stainless steel and several vanadium-base alloys. The results suggest that V-5Cr-5Ti has better resistance to fatigue than 316-SS in the temperature range of 25 to 400°C. At 400°C, the data also show that V-5Cr-5Ti out performs Vanstar alloys 7 and 8 over the entire range of strains investigated. Furthermore, the fatigue properties of the V-5Cr-5Ti alloy compare favorably to V-15Cr-5Ti (at 25°C) and Vanstar 9 (at 400°C) at strains greater than 1%. At lower strains, the lower fatigue resistance of V-5Cr-5Ti is attributed to the higher strengths of the V-15Cr-5Ti and Vanstar 9 alloys.

PROGRESS AND STATUS

Introduction

Low cycle fatigue tests were conducted on samples of V-5Cr-5Ti from Teledyne Wah Chang Ht. 832394 (ANL designation BL63) at temperatures of 25, 250, and 400°C and pressures less than 7.3×10^{-6} Pa (5.5×10^{-8} torr). In addition to these data, the effect of environment on fatigue properties at ambient temperatures was examined by conducting additional tests in a rough vacuum of ~ 2.6×10^{3} Pa (20 torr). The results are compiled in the form of tables and plots. Where data permit, comparisons are made between this V-5Cr-5Ti alloy and other vanadium-base alloys and 316 stainless steel.

Materials and Procedures

Specimens were fabricated from a 6.35 mm (0.25 in) thick plate of V-5Cr-5Ti produced by Teledyne Wah Chang (Heat 832394). The chemical composition (wt.%) of the plate was 5.1 Ti, 4.5 Cr, 310 ppm Si, 35 ppm C, 364 ppm O, 52 ppm N, and 1.1 ppm H with the balance being vanadium. The mechanical properties of this heat have been studied extensively at the Argonne National Laboratory (ANL), where this heat of material is referred to as BL63. The plate was received in the annealed condition (1 *h* at 1125°C) and specimens were fabricated with the geometry shown in Fig. 1. Following machining, the specimens were etched using a solution of 60% H_2O - 30% HNO_3 - 10% HF for approximately two minutes, wrapped in Ta foil, and annealed at 1125°C for 1 *h* in a vacuum of less than 1×10^{-5} Pa (10^{-7} torr). The resulting microstructure is shown in Fig. 2. An equiaxed grain structure is present within an average ASTM grain size of 6.

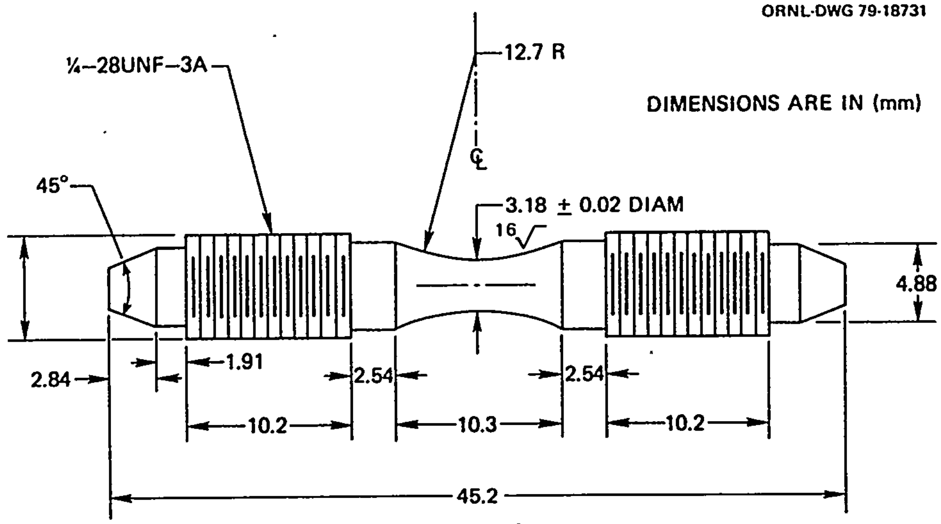


Fig. 1. Miniature hourglass fatigue specimen employed in fatigue testing. Dimensions are in millimeters.

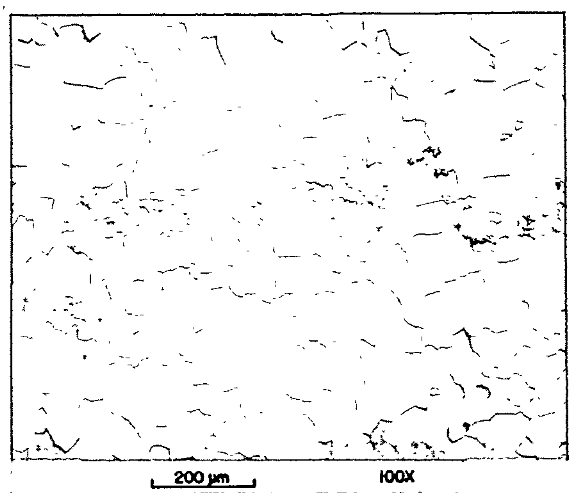


Fig. 2. Photomicrograph of V-5Cr-5Ti alloy (93-0991-1).

Tests were conducted on a servo-hydraulic test frame using a strain computer to convert diametral strain to an equivalent axial strain. The tests were conducted in axial strain control at a constant strain rate of 4×10^{-3}/s. During the course of testing, it was observed that V-5Cr-5Ti exhibits serrated yielding under some combinations of strain and temperature such that the strain range often had to be gradually increased to the desired level during the first 10-25 cycles. The presence of this behavior prevented testing at total strain ranges greater than 1.75% at the elevated temperatures and became more prominent as temperature increased. Typically, serrated yielding occurred at the onset of cycling in tests with a strain range ≥ 0.75% and would disappear within several hundred cycles, only to re-emerge near the end of the tests.

Heating was accomplished using RF induction, and temperatures were maintained within ±2°C of the desired setpoint. Initial tests at room temperature were conducted in a rough vacuum of ~ 2.6×10^{3} Pa (20 torr) that was used to maintain the cleanliness of the test chamber. All other experiments were initiated after a pressure of less than 7.3×10^{-6} Pa (5.5×10^{-8} torr) was obtained while at the desired test temperature. Pressures typically continued to drop to less than 2.0×10^{-6} Pa during cycling.

Experimental Results

The results of the fatigue tests have been listed in Table 1 and plotted in Fig. 3. The data were fitted to a power law expression originally suggested by Manson [1] and given by:

$$\Delta\varepsilon_t = AN_f^{-\alpha} + BN_f^{-\beta}$$

where, $\Delta\varepsilon_t$ = total strain range in %, N_f = number of cycles to failure, and A, B, α and β are material constants. The values of these constants can be found in Table 2. The data for α have values on the same order of magnitude as reported by Liu [2] for V-15Cr-5Ti, but must be viewed with caution since the data used to generate them came from tests in which the cyclic lives are relatively short. The values for ß also compare well with those reported by Liu for V-15Cr-5Ti, but the values of β for both V-15Cr-5Ti and V-5Cr-5Ti differ from the 0.5 to 0.6 often reported in engineering alloys.

Table 1. Summary of Test Conditions and Results for LCF Experiments Conducted on V-5Cr-5Ti (TWC Ht. 832394)

Spec. No.	$\Delta\varepsilon t$ (%)	Temp. (°C)	Nf	$\Delta\varepsilon p$ (%)a	$\Delta\varepsilon E$ (%)b	$\Delta\sigma$ (MPa)a	Pressure (Pa)
VA 05	0.49	25	134,923	≈ 0	0.49	58.8	2.6 x103
VA 04	0.59	25	49,367	0.011	0.579	711.3	2.6 x103
VA 03	0.732	25	22,165	0.018	0.714	882.7	2.6 x103
VA 07	0.98	25	5906	0.121	0.859	1016.6	2.6 x103
VA 02	1.54	25	2240	0.62	0.92	1068.3	2.6 x103
VA 06	2.04	25	1088	1.12	0.92	1116.1	2.6 x103
VA 16	0.77	25	136,829	0.033	0.74	921.5	≤ 7.3 x10-6
VA 14	1.02	25	37,379	0.138	0.882	1007.2	≤ 7.3 x10-6
VA 15	1.52	25	11,613	0.60	0.92	1033	≤ 7.3 x10-6
VA 20	0.78	250	206,642	0.11	0.67	805.4	≤ 7.3 x10-6
VA 18	1.00	250	74,381	0.253	0.747	826.7	≤ 7.3 x10-6
VA 19	1.38	250	30,476c	0.74	0.64	843.7	≤ 7.3 x10-6
VA 21	1.54	250	18,550	0.80	0.74	851.4	≤ 7.3 x10-6
VA 17	0.76	400	336,030	0.07	0.69	811.3	≤ 7.3 x10-6
VA 09	1.00	400	164,277	0.286	0.714	869.9	≤ 7.3 x10-6
VA 11	1.23	400	75,052	0.482	0.748	905.0	≤ 7.3 x10-6
VA 13	1.53	400	33,476	0.743	0.787	940.0	≤ 7.3 x10-6
VA 12	1.77	400	25,272	0.98	0.79	921.1	≤ 7.3 x10-6

Notes: (a) Measured from a loop near midlife. $\Delta\varepsilon_p$ = width of hysteresis loop at zero load.
(b) The quantity $\Delta\varepsilon_E = \Delta\varepsilon_t - \Delta\varepsilon_p$.
(c) Strain range dropped during test, resulting in unusually long cycle life. Datum plotted but not considered in determination of material constants.

Table 2. Material Constants in Coffin-Manson Equation for V-5Cr-5Ti Alloy

Temperature (°C)	Press. (Pa)	A	α	B	β
25	2.6 x 103	2.85	0.1464	50,093	1.493
25	≤7.3 x 10-6	2.384	0.0983	35,143	1.176
250	≤7.3 x 10-6	1.47	0.0646	2611	0.823
400	≤7.3 x 10-6	1.39	0.0552	611	0.638

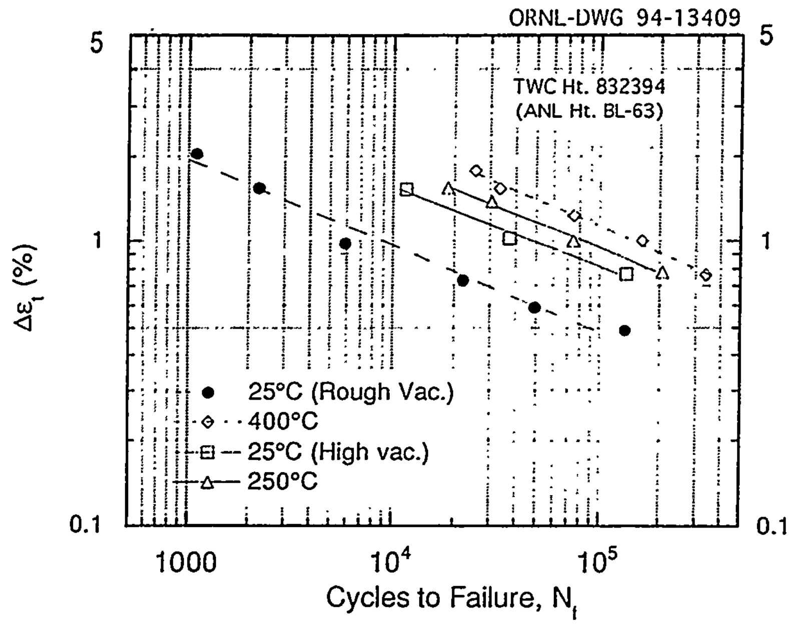


Fig. 3. Cyclic fatigue data for V-5Cr-5Ti tested at 25, 250, and 400°C in rough and high vacuums.

Two observations can be easily drawn from Fig. 3. First, the fatigue lives in high vacuum increase with increasing temperature over the range investigated. This increase in life varies from a factor of 1.5 to 4.4 times that observed at 25°C (refer to Table 3.). Swindeman [3] has reported similar results on niobium alloy D-43 where he observed increasing plastic strain resistance (*ie.*, life) at temperatures up to 871°C. Swindeman also noted that above 871°C, the magnitude of the increase began to decrease and it is likely that similar behavior would be observed in the V-5Cr-5Ti alloy. The second observation is that at room temperature there is a considerable effect of environment on the fatigue life. Between rough and high vacuum, there is an increase in life that ranges from a factor of about 5 to 6 (Refer to table 3.).

Table 3. Comparison of Cyclic Lives Under Various Conditions for Selected Strain Ranges

Nominal Δεt (%)	Nhv/Nrv at 25°C	N250/N25	N400/N25
0.75	6.17	1.51	2.46
1.00	6.33	1.99	4.39
1.53	5.18	1.60	2.88

Notes: (a) N_{hv}/N_{rv} is the ratio of observed life at 25°C in high vacuum to that observed in a rough vacuum.
(b) N_{250}/N_{25} is the ratio of fatigue life at 250°C to that at 25°C for tests conducted in a high vacuum.
(c) N_{400}/N_{25} is the ratio of fatigue life at 400°C to that at 25°C for tests conducted in a high vacuum.

In Figs. 4, 5 and 6, plots of the stress range as a function of cycle count (Δσ vs. N) are shown for select fatigue tests at 25°C and all those conducted at 250 and 400°C. In all the tests, the V-5Cr-5Ti alloy cyclically hardens up to the point of crack initiation. At 25°C, in most tests conducted in high vacuum, initiation takes place early and a considerable fraction of life is spent propagating a crack. Conversely, plots of the stress range as a function of cycle count for tests (at 25°C) conducted in rough vacuum suggest that crack initiation dominated and crack propagation was rapid.

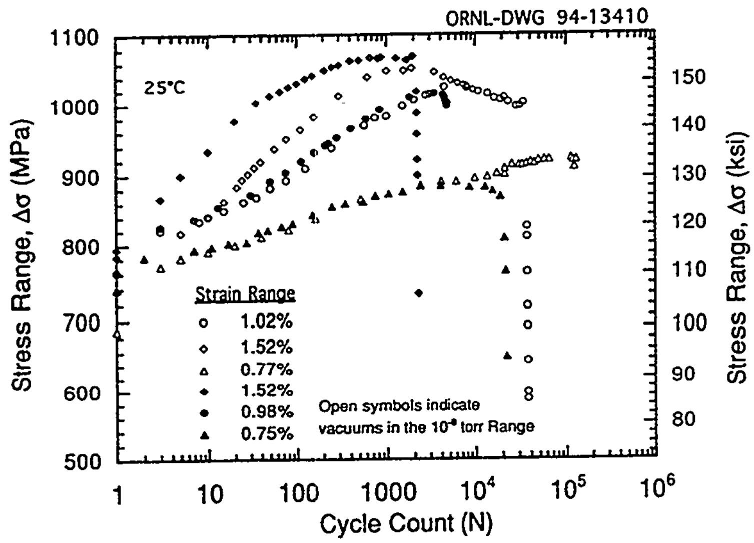


Fig. 4. Comparison of room temperature cyclic stress behavior of V-5Cr-5Ti alloy in rough and high vacuums.

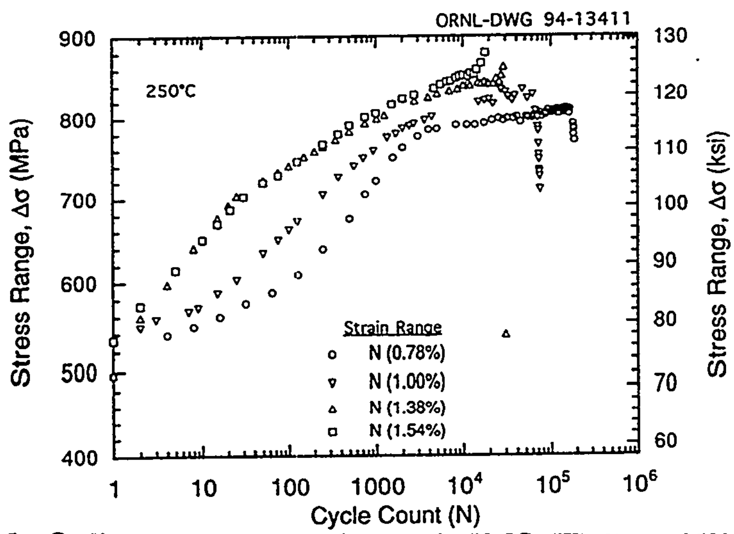


Fig. 5. Cyclic stress ranges vs cycle count for V-5Cr-5Ti alloy at 250°C.

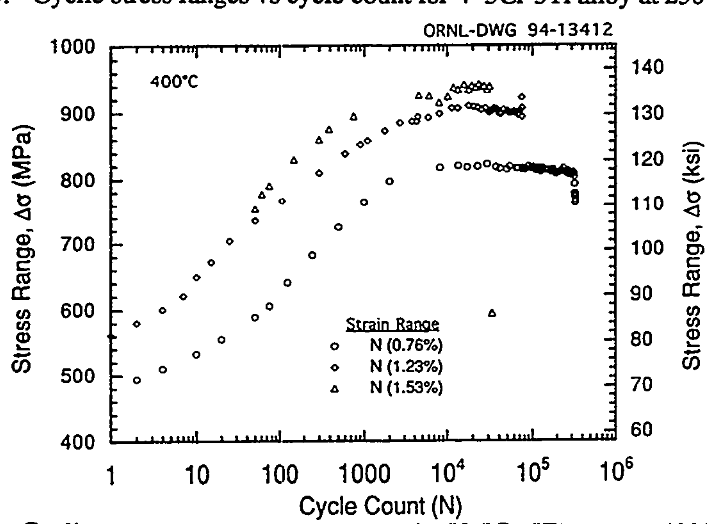
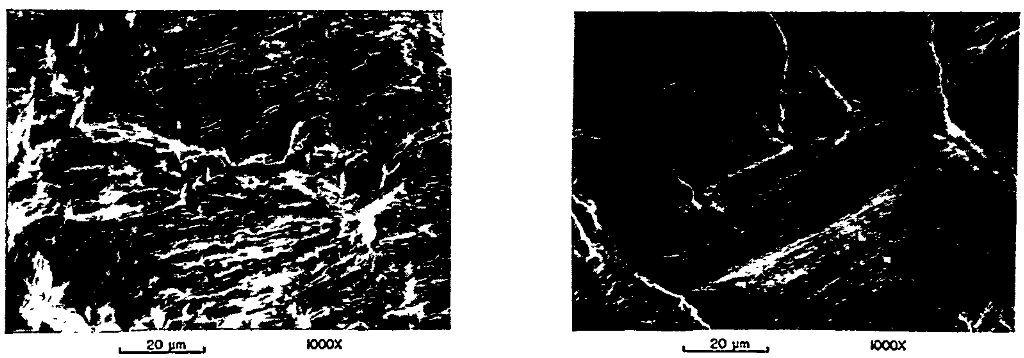


Fig. 6. Cyclic stress ranges vs cycle count for V-5Cr-5Ti alloy at 400°C.

Fatigue fracture surfaces from six specimens were examined using scanning electron microscopy (SEM) to better understand the nature of crack propagation and the effect of environment. In all tests, crack propagation appears to have occurred in a predominantly transgranular fashion with small amounts of intergranular fracture. Intergranular fracture typically occurred when grain boundaries were oriented such as to trap an approaching crack.

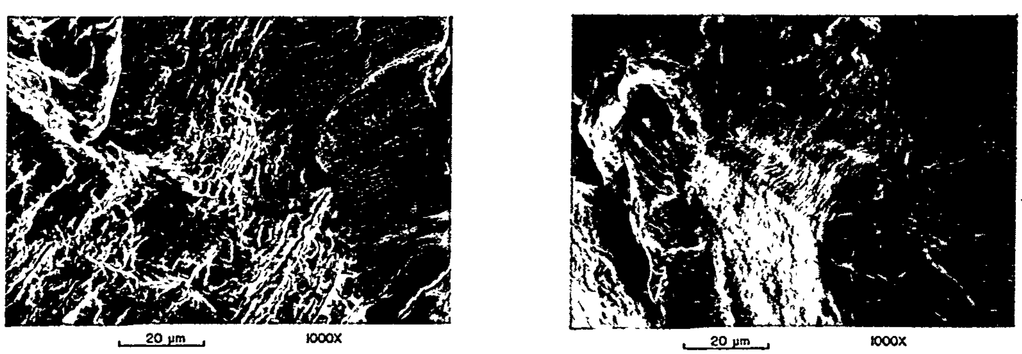
In Fig. 7, SEM micrographs are shown for tests conducted in rough and high vacuums at a nominal total strain range of 0.75%. The fracture morphology for the test conducted in rough vacuum (Fig. 7a) shows a courser striation spacing in combination with secondary cracking and a more brittle appearance than that observed for the test conducted in high vacuum (Fig. 7b). When viewed at a higher magnification (refer to Fig. 8a), the area shown in Fig. 7b shows signs of ductility on a microscopic scale, which is not present for the test in rough vacuum (*cf.* Fig. 8b),. This microductility was also observed in tests conducted at elevated temperatures conducted in high vacuum. With increasing temperatures, the amount of ductility appears greater, as one might expect.

The fine dipples creating the appearance of microductility on some of these fracture surfaces are associated with very fine particles. Previous studies have shown that the primary precipitates identified in vanadium alloys are titanium oxycarbonitrides [4] and it is assumed that these are present here. In other areas, the average size of features associated with this phenomena suggest that crack face welding has occurred during the compressive portion of the strain cycle.



(a) (b)

Fig. 7. Scanning electron microscopy of RT fatigue fracture surfaces indicates differences in the fatigue crack propagation process for a nominal 0.75% strain range. (a) Sample 03 - tested in rough vacuum (U 007477). (b) Sample 16 - tested under high vacuum (U 007479).



(a) (b)

Fig. 8. Scanning electron microscopy of RT fatigue fracture surfaces from tests conducted at a nominal 0.75% strain range. (a) Sample 16 - tested under high vacuum showing ductility on a microscopic scale (U 007476). (b) Sample 03 - tested in rough vacuum (U 007480).

DISCUSSION OF RESULTS

Environmental Effects

Several possible mechanisms exist which may explain the reduction in life observed in experiments conducted in a rough vacuum, including; (1) pickup of O and N interstitials, (2) changes in the crack initiation and/or growth mechanisms, and (3) hydrogen embrittlement arising from the interaction of moisture with the alloy. Oxygen and nitrogen are potent hardeners, but it is unlikely that diffusion rates of these species are sufficiently high at 25°C to have penetrated into the alloy and embrittled the alloy to any notable extent. Korth and Schmunk [5] conducted tests in air on Vanstar alloys 7, 8, and 9 at 400°C and found no change in oxygen content in post-test analyses of their samples. Hence, negligible oxygen (and nitrogen) diffusion at 25°C can be assumed.

On the other hand, oxygen or moisture present in the vacuum chamber may have formed a brittle oxide layer on any freshly exposed surfaces, such as those created by the rupture of a surface oxide during plastic deformation in each cycle or at persistent slip bands. Oxidation at persistent slip bands would result in earlier initiation and the repeated process oxide formation and rupture at a crack tip would lead to increased rates of crack growth. Furthermore, the formation of an oxide layer on the crack faces may prevent rewelding of these surfaces during the compression portion of the strain cycle, again, leading to increased crack growth rates. From the results shown in Fig. 4, a combination of these mechanisms is likely.

As Fig. 4 indicates, at the two lower strain ranges (nominally 0.75 and 1.0%) the data show little difference between rough and high vacuum up to point of maximum $\Delta\sigma$. At a nominal strain range of 1.5%, there is a notable difference in the hardening behavior for the majority of life. The reason for this is not known. The curves suggest that initiation occurs at approximately the same cycle count in the 1.53% strain range tests and that the difference in life is the result of a difference in crack growth rates. At the 1% strain range, it appears that differences in both the rate of initiation and crack growth are present. At the lowest strain range (0.75%), the curves suggest that both crack initiation and crack growth proceed more slowly in high vacuum. Hence, these curves suggest that the failure processes are complex and dependent upon the strain range. Additional testing would be required to estimate the relative contributions of each mechanism at work.

Surface oxides function as a barrier to hydrogen, but if it is removed by polishing, scratching, or chemical etching, hydrogen may be introduced from an aqueous medium, moisture in air, or an acid [6]. Cycling prior to crack initiation and during crack growth may have created and maintained an avenue for airborne moisture to reach and oxidize the alloy with the release and absorption of free hydrogen.

Comparison to Competing Alloys

An attempt has been made to compare data generated on V-5Cr-5Ti to other alloys under consideration for use in fusion reactors, including Vanstar alloys at 400°C, V-15Cr-5Ti alloy at 25°C, and 316 stainless at 25°C [7] and 430°C [6]. In most cases, test conditions are not identical to those used in the current study and a very limited data base exists making any comparison difficult.

In Fig. 9, a comparison of the room temperature low cycle fatigue properties of the V-5Cr-5Ti alloy is made with both 316 stainless steel [7] and a V-15Cr-5Ti alloy [2]. From the limited data, both the vanadium alloys appear to have better plastic strain resistance than does 316 stainless. The data may suggest that the endurance strain in the 316 SS is 0.25%, whereas estimates for the V-5Cr-5Ti and V-15Cr-5Ti are 0.5% and 0.75%, respectively. At strains greater than 1%, the data for the V-base alloys appear to converge, as would be expected since the ductilities do not differ by more than two percent [8] and strain controls life in this regime. The difference found at longer lives (lower strains) is attributed to increased strength of the V-15Cr-5Ti alloy and the resulting reduction in plastic strain ranges. Loomis et al., [8] report that both the yield and tensile strengths of the 5Cr alloy are 71-72% of those for the 15% alloy (σ_{ys} = 387 vs. 545; σ_{uts} = 454 vs. 634 MPa).

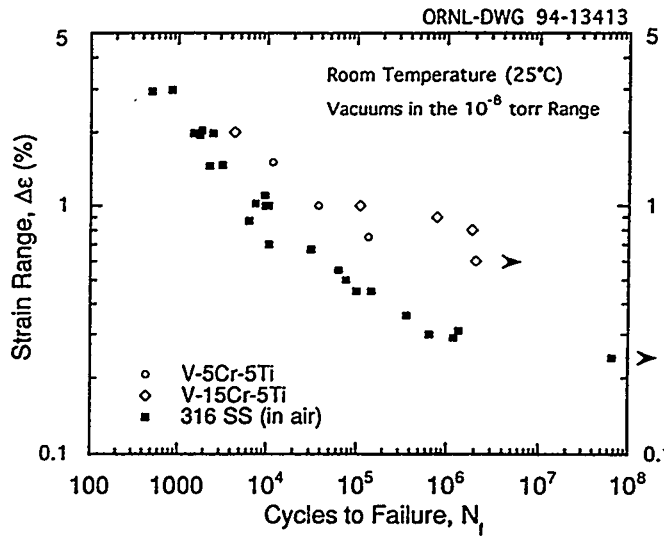


Fig. 9. Comparison of fatigue properties of V-5Cr-5Ti and V-15Cr-5Ti alloys to 316-SS at 25°C. Data for 316 stainless steel were obtained from Ref. 7 and those for V-15Cr-5Ti were obtained from Ref. 2.

Korth and Schmunk [5] tested Vanstar alloys 7, 8 and 9 in air at 400°C using a diametral extensometer and controlling the equivalent axial strain. Their data show little difference between the number of cycles, N_0, at initiation and the number of cycles to failure, N_f ,and they suggested that atmosphere had little effect on test results. In light of the results for V-5Cr-5Ti alloy, it is likely that N_f for tests conducted in vacuum would have been much greater. Notwithstanding this difficulty, the data are plotted in Fig. 10 and several observations can be drawn. First, at strain ranges of 1% or more, the V-5Cr-5Ti alloy shows better resistance to fatigue damage than Vanstar 9. At lower total strain ranges, the opposite is true. The better performance of Vanstar 9 at lower total strain ranges is, again, attributed to its higher yield strength (ie., 360 MPa [5] vs 250 MPa [8]) and the resulting reduction in plastic strains.

A second observation is that the V-5Cr-5Ti out performs alloys Vanstar 7 & 8 at all strain ranges shown. A comparison of the tensile data of Korth and Schmunk [5] on the Vanstar alloys to that of Loomis et al. [8] on V-5Cr-5Ti indicates that the V-5Cr-5Ti has greater strength than the Vanstar alloys 7 & 8 at 400°C. However, the authors believe that the testing of Vanstar alloys 7, 8, and 9 in vacuum would result in higher cyclic lives and probably eliminate much of the observed differences.

In Fig. 10, a comparison of the low cycle fatigue properties of the V-5Cr-5Ti alloy at 400°C is also made with 316 stainless steel [9] tested at 430°C. In this case, Grossbeck and Liu used the same specimen geometry and test method as was used in testing the V-5Cr-5Ti alloy such that the data should be very easily comparable with the exception of temperature. Again, the results suggest that the V-5Cr-5Ti alloy has better low cycle fatigue properties than does the 316 stainless around 400°C. While insufficient data exist to allow an endurance strain to be determined from the V-5Cr-5Ti alloy, it should be in the 0.5-0.6% range in comparison to the 0.3-0.4% value for the 316 stainless.

CONCLUSIONS

In-vacuum low cycle fatigue tests have been conducted on unirradiated V-5Cr-5Ti tested at temperatures of 25, 250, and 400°C. A comparison of the fatigue data generated in rough and high vacuums shows that a pronounced environmental degradation of the fatigue properties exists in this alloy at room temperature. Fatigue life was reduced by as much as 84%. The cyclic stress range data and SEM observations suggest that this difference is due to a combination of differences in rates of crack initiation and subsequent crack growth. The relative contribution of each difference is dependent upon the strain range.

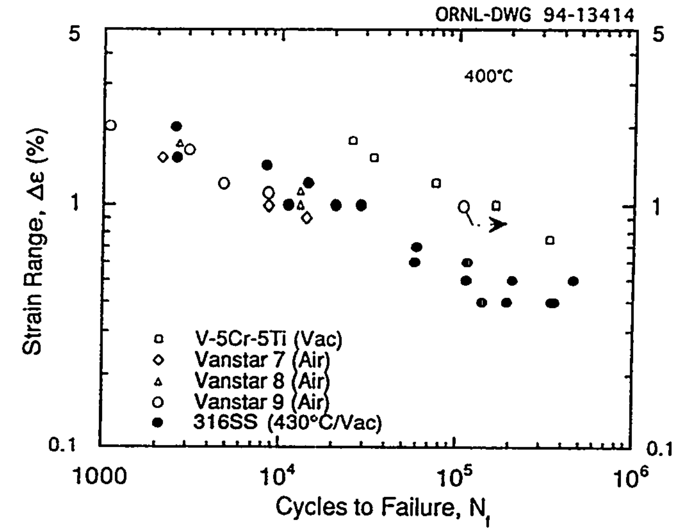


Fig. 10. Comparison of fatigue data for vanadium-base alloys and 316 stainless steel at temperatures 400 to 430°C. Data for 316 stainless were obtained from Ref. 9. Data for Vanstar alloys were obtained from Ref. 5.

In high vacuum, the fatigue results also show a trend of increasing cyclic life with increasing temperature between 25 and 400°C. From the limited data available, life at 250°C averages 1.7 times that at 25°C, and at 400°C, life averages 3.2 times that at 25°C. Like the environmental effects at 25°C, the effect of temperature seems to be a function of strain range at each temperature.

The total strain range and cycles to failure were analyzed using a power law correlation and compared to 20% cold-worked 316 stainless steel and several vanadium-base alloys. The results suggest that V-5Cr-5Ti has better resistance to fatigue than 316-SS in the temperature range of 25 to 400°C. At 400°C, the data also show that V-5Cr-5Ti out performs Vanstar alloys 7, and 8 over the entire range of strains investigated. Furthermore, the fatigue properties of the V-5Cr-5Ti alloy compare favorably to V-15Cr-5Ti (at 25°C) and Vanstar 9 (at 400°C) at strains greater than 1%. Differences seen at higher lives (lower strains) are attributed to the higher strength of the V-15Cr-5Ti and Vanstar 9 alloys.

FUTURE WORK

Low cycle fatigue studies are complete on this heat of V-5Cr-5Ti. Additional LCF tests may be conducted on the new 500 kg heat of this alloy currently being melted by TWC for ANL. The emphasis of future testing will likely shift to fatigue crack propagation measurements on this new heat of material.

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