Journal of Nuclear Materials 122 & 123 (1984) 850-854
North-Holland, Amsterdam

TENSILE AND LOW-CYCLE FATIGUE MEASUREMENTS ON CROSS-ROLLED TUNGSTEN AT 1505 K

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Tungsten continues to be considered for use in fusion reactors because of its mechanical properties, good thermal shock resistance, and relatively high thermal conductivity. Low-cycle fatigue and tensile tests have been made at 1505 K on specimens fabricated from 12.7-mm thick cross-rolled tungsten plate which was prepared by a powder metallurgy process. All tests were made in vacuum, and the fatigue tests were made in strain control. The experimental fatigue data agree fairly well with the "universal slopes" equation, giving a slightly lower number of cycles to fail than predicted by the equation for a given strain range. Details of the test procedure are reported along with the experimental results. These data should support continued design work where tungsten is considered for application in pulsed reactor systems.

1. INTRODUCTION

Materials are needed for beam dumps, protector plates, and collector plates in magnetic divertor assemblies for fusion reactors. These components will be exposed to high heat loads and subjected to large temperature and stress gradients. Physical sputtering rates will be high due to the impinging particle fluxes and a neutron flux will be present as well. Radiation damage will result in swelling, embrittlement, and creep of the plate materials. Conditions may include both pulsed and steady state operation. Taken together, these conditions represent one of the most severe environments to be found in a fusion reactor. The refractory metals have been recommended for use in these conditions, with tungsten being slightly favored due to its high melting point. Although the use of tungsten in the plasma chamber is detrimental to the plasma due to the enhanced bremsstrahlung that results, it is still considered attractive for areas where it would not lead to bulk plasma contamination. As an example, the divertor channel on INTOR would be lined with tungsten tile to carry the high surface heat load. Considerable mechanical property data exist for tungsten, but in many cases the process history of the material is not clearly identified. Low-cycle fatigue data are available up to 1088 K, but not above that temperature. Hence, the data presented here should be of interest for reactor designs in which tungsten would be required to function above 1088 K.

Low-cycle fatigue measurements at both room temperature and 1088 K and tensile data at the higher temperature from this program have been reported.[1] Data are reported here for low-cycle fatigue and tensile measurements at 1505 K in vacuum.

2. EXPERIMENTAL PROCEDURE

The specimens were prepared from powder metallurgy tungsten plate, 14 mm thick, which was obtained from GTE Sylvania. The plate material was prepared from 99.9% purity starting material and was cross-rolled in the

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reduction process to provide maximum uniformity of properties in the plane of the plate. Specimens were prepared from the plate by Thermo Electron Corporation using grinding techniques followed by a final electropolish to remove surface scratches. As noted previously,[1] specimen blanks were cut from the cross-rolled plate without regard to longitudinal or transverse direction due to the lack of observed directionality in the grain structure and initial strain measurements. Hourglass and uniform gage specimens were used for the fatigue and tensile measurements, respectively. The gage section of the hourglass specimens had an hourglass radius of 50.8 mm and a minimum diameter of 5.08 mm. The uniform gage specimens were 6.35 mm in diameter by 19.05 mm long in the test section. Both specimen configurations incorporated button-head ends for gripping the specimens during the tests.

A larger vacuum chamber was required for testing at 1505 K than had been used at 1088 K. The current chamber and fatigue frame are shown in Figure 1. Inside dimensions of the chamber are 450 mm diameter by 696 mm, for a volume of approximately 110 L. A die set alignment fixture is assembled inside of the chamber, in contrast to the previous system where a small vacuum chamber was assembled inside the four corner posts of the fatigue frame which provided alignment as well as load transmission. A hydraulic actuator penetrates into the vacuum chamber through the bottom flange. Multiple O-rings seal against the actuator shaft, and differential vacuum pumping is applied between the middle seals to minimize leakage into the chamber. The diffusion pump and liquid nitrogen cold trap assembly result in a retained pumping speed of 600 L/s. The vacuum detection gage is located

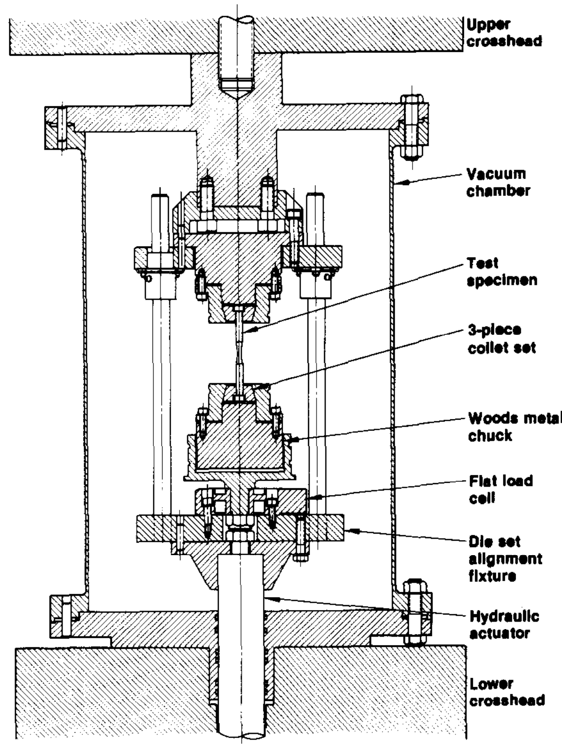

FIGURE 1
Cross section of vacuum fatigue chamber showing the die set alignment fixture installed

in the main body of the chamber, well removed from the pumping system. Ultimate vacuum levels of less than 1.3×10^{-5} Pa have been attained with the system. Specimen loading and other operations are handled through two 203-mm diameter side access ports. A 152-mm diameter viewing port is included for ease of operation.

A diametral extensometer, positioned at the minimum diameter of the gage section of the specimen, was used on all tests at 1505 K. Strain-controlled, fully-reversed uniaxial fatigue tests were conducted using a closed-loop servohydraulic fatigue system. Fatigue tests were run in strain control utilizing a triangular wave form and with the frequency adjusted to maintain a constant strain rate of $4 \times 10^{-3}\ s^{-1}$. Tensile data were obtained on the same system in stroke (displacement) control by adjusting the crosshead velocity to obtain a constant strain rate of $8.3 \times 10^{-5}\ s^{-1}$.

Induction heating was used. A gap was formed at the center of the induction coil to allow for insertion of the extensometer. Type K thermocouples were used initially to establish the temperature profile on the specimens and to ensure that the ends of the specimens did not become too hot. Active temperature monitoring and control during the tests were accomplished with an IRCON infrared two wavelength optical pyrometer.

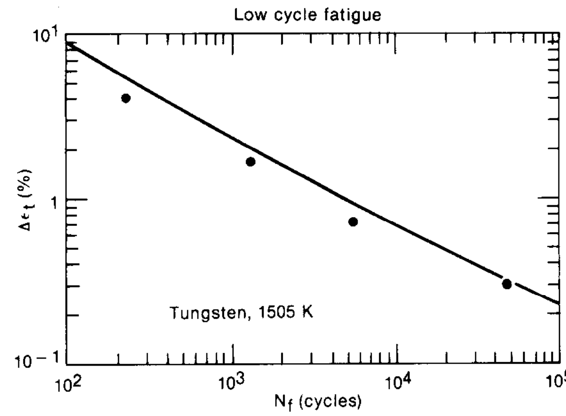

FIGURE 2
Tungsten low-cycle fatigue data at 1505 K. The line gives the prediction of the universal slopes equation

3. RESULTS AND DISCUSSION

Test data for low-cycle fatigue measurements on tungsten at 1505 K are presented in Table 1 and in Figure 2. Data were obtained only for the as-received condition due to the small number of specimens available. The data agree fairly well with the universal slopes equation[2] which was used to select the strain ranges for each of the tests. The stress-strain hysteresis loops which were recorded during the tests display a considerable amount of serrated yielding. Examination of hysteresis loops for 1088 K data which were reported previously suggest that a small amount of the effect was observable on some of the tests at the lower temperature. At 1505 K, however, the effect is very noticeable on the first quarter cycle and becomes more

TABLE 1. TUNGSTEN LOW-CYCLE FATIGUE DATA, 1505 K

Specimen Number	$\Delta\epsilon_t$ (%)	$\Delta\epsilon_p{}^a$ (%)	$\Delta\sigma^a$ (MPa)	$\sigma_{TEN}{}^a$ (MPa)	N_f	t (h)
5-9	0.30	0.21[c]	273[c]	133[c]	48,214[b]	19.79
5-10	0.70	0.55	292	144	5,695	5.42
5-6	1.70	1.53	338	166	1,313	2.97
5-7	4.02	3.87	398	197	231	1.23

a. Properties at $N_f/2$; $\Delta\epsilon_p$ = plastic strain, σ_{TEN} = tensile stress, $\Delta\sigma$ = stress range, $\Delta\epsilon_t$ = total strain range, N_f = number of cycles to fail, and t = time to fail.

b. Test interrupted by error signal, on restart specimen showed extreme hardening, test terminated.

c. Properties at cycle 34,604.

pronounced with additional cycles. Serrated yielding in low-cycle fatigue has been observed in other materials such as Type 316 stainless steel and Inconel 718, although the basis for it may be different from the present case.[3] In tungsten it is thought to be due to dislocation locking at solute carbon atoms.[4] The effect is more pronounced at 1505 K than at the lower test temperature due to the higher diffusivity of carbon in tungsten at the higher temperature.

The vacuum level in the test chamber was reduced to nominally 1.3 x 10^{-5} Pa before specimen heating began. With the gage section of the specimen at test temperature and the extensometer reading stabilized, the pressure in the chamber was usually a factor of 10 to 20 higher. For the high temperature and low pressure of these tests oxygen contamination was not considered to be a problem. According to several authors,[5,6] any oxide formation at 1505 K in a vacuum should result in the immediate volatilization of the oxide molecule. One might expect, though, that oxide formation might be observed along the shank of the specimens where the temperature was lower. The shiny appearance of specimen surfaces after the tests were completed indicates that there was not sufficient oxygen present for any noticeable oxide scale formation.

Tensile test data were obtained for two specimens: one for the as-received wrought condition and one for recrystallized (1755 K anneal for 1 h in vacuum) material. The data which are given in Table 2 are within the accepted range for published data.[7]

4. CONCLUSIONS

- The universal slopes equation gives fair agreement with low-cycle fatigue data at 1505 K for cross-rolled tungsten and could be used for a first approximation where tensile data are available.
- Tensile test data obtained for both as-received and recrystallized conditions agree with published data.

ACKNOWLEDGMENT

This work has been supported by the U.S. Department of Energy under DOE Contract No. DE-AC07-76ID01570.

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TABLE 2. TUNGSTEN TENSILE DATA, 1505 K

Material Condition	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Total Elongation (%)	Reduction In Area (%)
As-received	326	273	9.5[a]	--
Recrystallized	188	61.7	42	51

a. Calculated based on recorded crosshead travel.

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