Thermophysical and Mechanical Properties for Ta-8%W-2%Hf (6/30/98 draft for APEX)

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The key thermophysical and mechanical properties for Ta-8%W-2%Hf (alloy T-111) are summarized in the following. This solid solution alloy was developed in the early 1960s and was commercially produced by several vendors [1]. Most of the development work on refractory metals stopped in the early 1970s due to the suspension of funding for nuclear space power systems and the decision to utilize reusable surface ceramic tiles rather than coated refractory metals for the Space Shuttle [2]. The T-111 alloy is presently not being produced due to lack of demand, and there is some concern that a "relearning" process would be needed before the alloy could once again be reliably produced (based on problems with a recent attempt to produce the tantalum alloy T-222) [1]. The alloy T-222 has a composition of Ta-10%W-2.5%Hf-0.01%C, and has somewhat superior mechanical strength compared to T-111 although the data base is not as comprehensive.

Tantalum alloys are susceptible to hydrogen embrittlement, as are its Group V-A siblings vanadium and niobium [3]. All of the Group V-A refractory alloys are ductile at room temperature, whereas the group VI-A refractory alloys (Mo and W) are generally brittle at room temperature. All refractory metals suffer from well-known oxidation problems at elevated temperatures (>500˚C). Therefore, either vacuum or an inert cover gas are required during elevated temperature processing (hot working, welding, etc.). Tantalum has a melting point of 2996˚C and a density of 16.7 g/cm^3 at room temperature.

All high-temperature refractory alloys are generally designed to be used in the stress-relieved condition rather than the fully recrystallized condition, in order to take advantage of the higher strength present in the stress-relieved condition. The recrystallization temperature depends on the amount of cold- or warm-work and also on the exposure time. The temperature to fully recrystallize 75% cold-worked alloy T-111 has been reported to be 1650˚C for a 1 hour anneal [4]. The enhanced diffusion associated with irradiation would cause a significant decrease in the recrystallization temperature, particularly is the operating stress on the component is significant. For design purposes, the recrystallized strengths should be used in order to provide an adequate safety margin in the event of radiation-enhanced recrystallization.

1. Ultimate tensile strength (unirradiated)

The ultimate tensile strength for Ta-8%W-2%Hf (alloy T-111) has been measured by several researchers. Dynamic strain aging occurs at temperatures between ~500 and 1000˚C for typical tensile strain rates of $\sim 10^{-3}\ s^{-1}$, which produces a local maximum in the ultimate strength in this temperature range. Figure 1 summarizes some of the ultimate tensile strength (UTS) data obtained in tensile tests on stress-relieved and recrystallized specimens [1,4-6]. Using the data summarized in the Aerospace Structural Metals Handbook [4] (filled square symbols in Fig. 1), the least squares fitted equation for the ultimate tensile strength of recrystallized T-111 over the temperature range of 20-1500˚C is

$$\sigma_{UTS}(\mathrm{MPa})=630 - 1.532*T +0.003388*T^2 -2.807e\text{-}06*T^3 +7.338e\text{-}10*T^4$$

where the temperature (T) is in ˚C. The correlation coefficient for this equation is R=0.988.

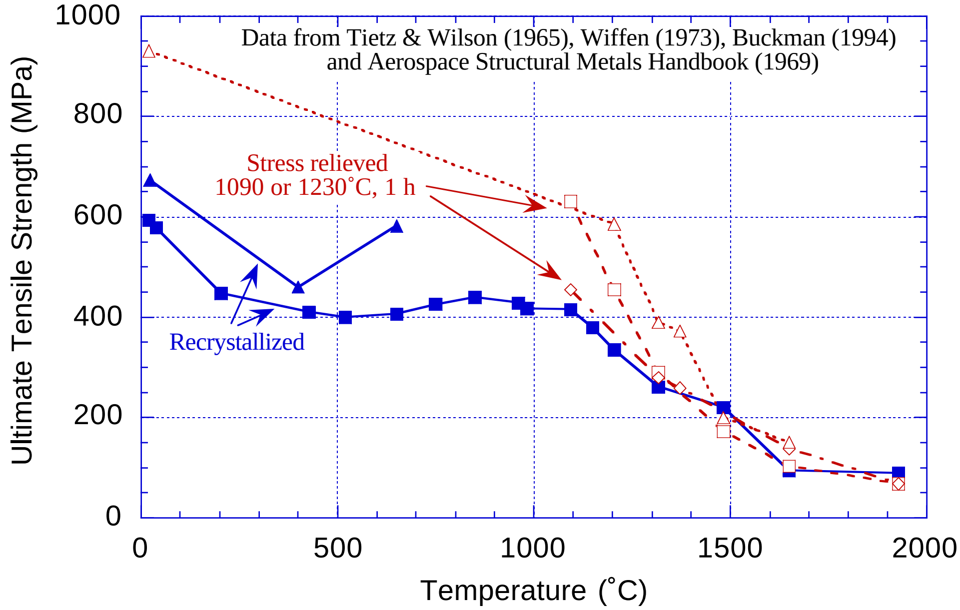

Fig. 1. Ultimate tensile strength of unirradiated Ta-8W-2Hf [1,4-6].

2. Yield strength (unirradiated)

Figure 2 summarizes the yield strength data obtained on stress-relieved and recrystallized specimens of Ta-8%W-2%Hf (alloy T-111) [4-6]. Using the data summarized in the Aerospace Structural Metals Handbook [4] (filled square symbols in Fig. 2), the least squares fitted equation for the yield strength of recrystallized T-111 over the temperature range of 20-1500˚C is

$$\sigma_Y(\text{MPa}) = 612 - 1.743*T + 0.003585*T^2 - 3.076e\text{-}06*T^3 + 8.819e\text{-}10*T^4$$

where the temperature (T) is in ˚C. The correlation coefficient for this equation is R=0.996.

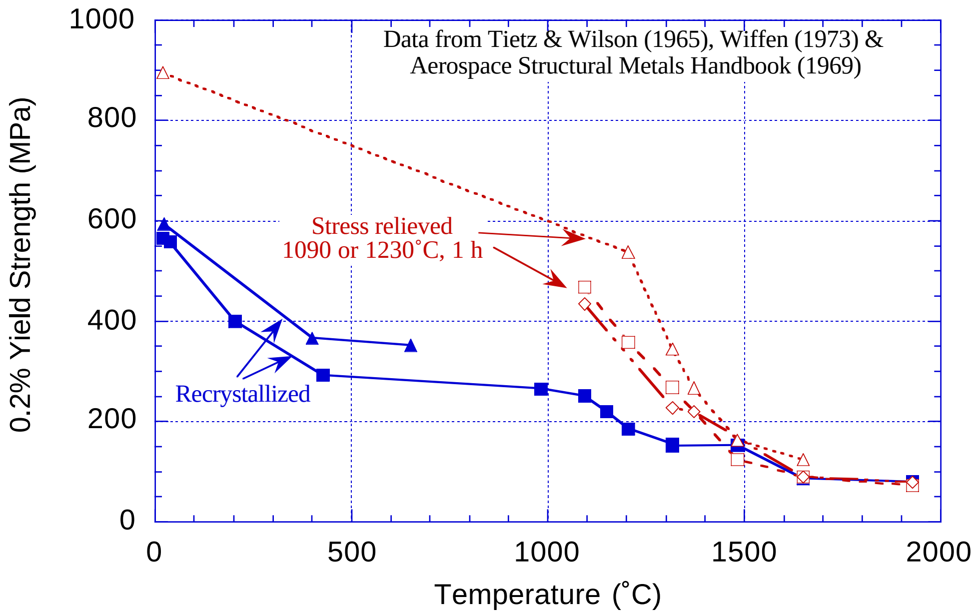

Fig. 2. Yield strength of unirradiated Ta-8W-2Hf [4-6].

3. Yield and ultimate strength (irradiated)

There have been few studies on irradiated T-111, with no known studies at temperatures above 650˚C [7]. Neutron irradiation causes a pronounced increase in the yield and ultimate tensile strength of Ta-8%W-2%Hf (alloy T-111) at temperatures below ~650˚C. The yield and ultimate strength increased to ~1250 MPa for a specimen tested at ~400˚C following fast reactor irradiation at ~410˚C to 1.9×10^{26} n/m^2 (E>0.1 MeV), which corresponds to a dose of ~2.5 dpa [6,7]. The yield and ultimate strength were ~1000 MPa for a corresponding irradiation and test temperature of ~640˚C and a similar dose [6]. Only a modest amount of radiation hardening was observed in Ta-10W irradiated at 800˚C, whereas severe radiation embrittlement occurred in a similar specimen irradiated at 350˚C [8]. The yield strength of solution annealed Ta-10W irradiated at 800˚C to a dose of ~2.5 dpa was reported to be 300 MPa compared to an unirradiated value of ~220 MPa, although the sample was apparently embrittled either by radiation or interstitial solute pickup (total elongation ~2%) [8]. This very limited tensile data base is consistent with radiation hardening results obtained on other BCC alloys (in particular vanadium alloys), where significant radiation hardening occurs at temperatures below 0.3 T_M (~700˚C for Ta). There is a clear need for mechanical property data on Ta alloys at temperatures ≥700˚C in order to further investigate radiation hardening and embrittlement effects. There are no known Charpy impact or fracture toughness measurements on irradiated Ta alloys.

4. Uniform and Total Elongation, Reduction in Area (unirradiated and irradiated)

There are very few reports of the uniform elongation in unirradiated or irradiated T-111 specimens. Figure 4 summarizes the unirradiated total elongation data obtained on stress-relieved and recrystallized specimens of Ta-8%W-2%Hf (alloy T-111) [4-6]. Wiffen [6] has reported on the uniform and total elongation of recrystallized T-111 following fast reactor irradiation to 1.9×10^{26} n/m^2 (E>0.1 MeV) at 410 and 640˚C (corresponding damage level ~2.5 dpa). The unirradiated elongations were 16-22% for test temperatures between 20 and 650˚C. The uniform elongation decreased to <0.5% following irradiation at 410˚C, and decreased to 1.9% following irradiation at

640˚C. The total elongations decreased to 4.5 to 10% following irradiation. The corresponding reduction in area following irradiation ranged from 36% for irradiation and testing at ~410˚C to 65% for irradiation and testing at ~640˚C. The unirradiated reduction in area ranged from 81 to 99% for testing at 20 to 650˚C [6]. The total elongation of Ta-10%W was zero (brittle failure) following irradiation to a dose of 0.1 dpa at 350˚C, and ~2% after a dose of ~2.5 dpa at 800˚C, where the tensile testing was performed at the irradiation temperature [8].

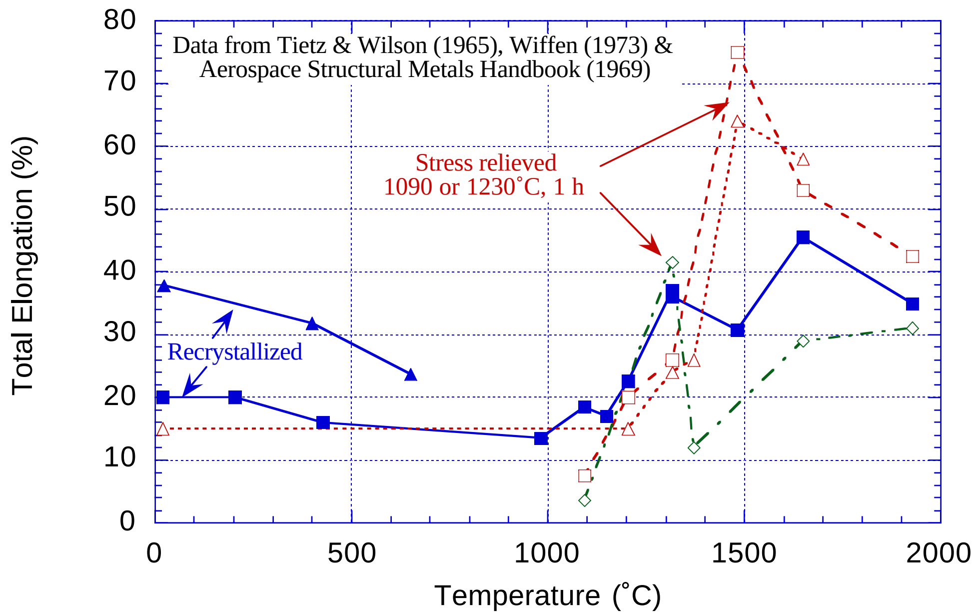

Fig. 3. Total elongation of unirradiated Ta-8W-2Hf [4-6].

5. Elastic constants

Young's modulus has been measured from -100 to 2000˚C for T-111 [4,5]. As shown in figure 4, the temperature-dependent Young's modulus for T-111 is comparable to that for pure Ta. The shear modulus (G) and Poisson's ratio (ν) of T-111 apparently have not been measured. Based on the measurements by Farraro and McLellan, the least-squares fitted polynomial expression for the elastic constants of pure Ta at temperatures above 700 K are [9]

$$E_Y=((1.69 - 8.22\times10^{-5}*T-1.66\times10^{-8}*T^2)\pm0.051) \times 10^{11} \text{ Pa}$$

$$G=((0.774 - 1.73\times10^{-4}*T)\pm0.016) \times 10^{11} \text{ Pa}$$

where the temperature is given in Kelvin. According to the measurements by Farraro and McLellan [9], Poisson's ratio equals 0.273 for pure Ta at room temperature. This value is somewhat lower than what is recommended in the ASM Metals Handbook (10th edition, Vol. 2), ν=0.35 at room temperature. Poisson's ratio at elevated temperatures can be obtained using the well-known relation $\nu=(E_Y/2G) - 1$.

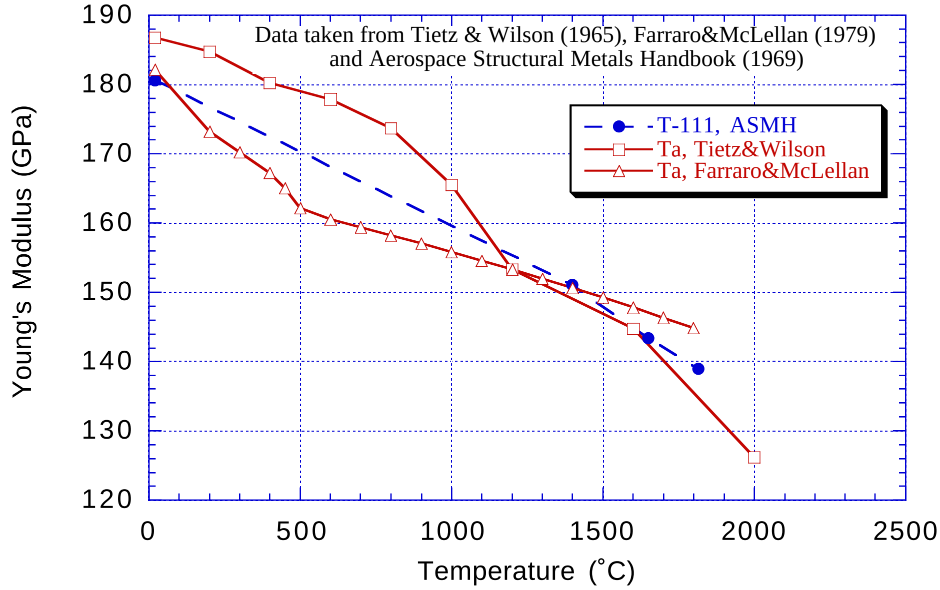

Fig. 4. Comparison of Young's modulus for unirradiated Ta-8W-2Hf and tantalum [4,5,9].

6. Stress-rupture and Creep

There have been numerous studies of the creep and stress-rupture behavior of unirradiated T-111 at temperatures up to 1600˚C (0.57 T_M) [10-12], but there are no known irradiation creep studies. The stress to produce 1% strain in T-111 in 1000 h is ~110 MPa at 1100˚C and ~50 MPa at 1250˚C [11]. Using a 1000 h creep-rupture stress level of 100 MPa as a guideline, the maximum operating temperature of T-111 is 1150-1200˚C [11]. Using the more conservative creep criterion of 1% plastic strain, the maximum operating temperature of T-111 for an applied stress of 100 MPa is 1000˚C for long-term (7 year) operation [10].

9. Thermal expansion, specific heat, thermal conductivity and electrical resistivity

Several thermophysical properties for T-111 have been measured from room temperature to ~1300˚C. The mean coefficient of thermal expansion (α_{th}) is very similar to that of pure Ta and Ta-10W, and varies from 5.9 ppm/˚C at room temperature to 7.6 ppm/˚C at 1650˚C [4,5,11]. The specific heat at constant pressure (C_P) is ~150 J/kg-K at 20˚C [4]. The electrical resistivity of T-111 ranges from 217 nΩ-m at room temperature to 665 nΩ-m at 1180˚C [4]. As shown in Fig. 5, the thermal conductivity varies from ~42 W/m-K at room temperature to ~56 W/m-K at 1350˚C. Using the Aerospace Structural Metals Handbook data, the thermal conductivity can be described by the following equation:

$$K_{th}\ (\text{W/m-K}) = 41.0 + 0.020\ T - 6.32\times10^{-6}\ T^2 \qquad \text{(temperature in ˚C)}$$

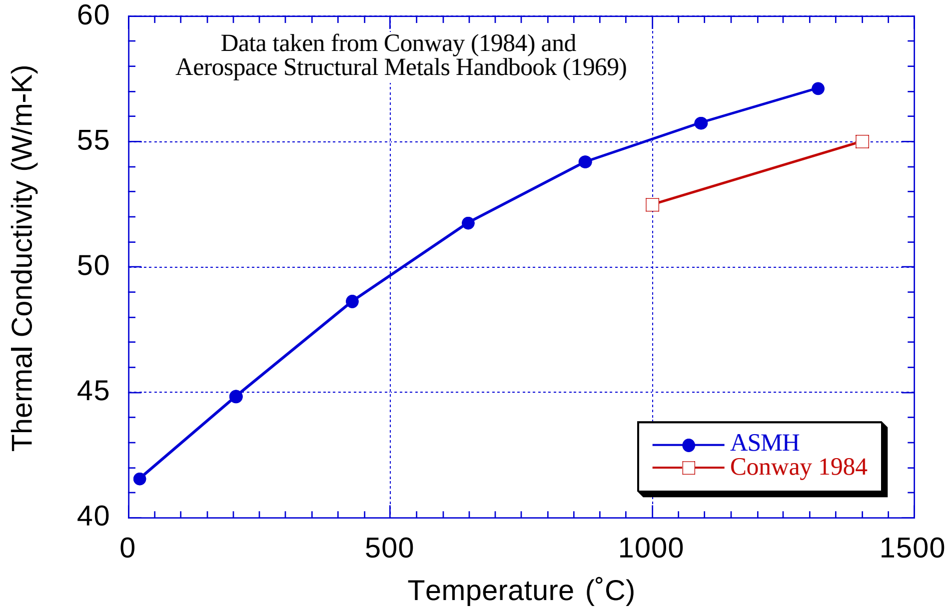

Fig. 5. Thermal conductivity of unirradiated Ta-8W-2Hf [4,11].

10. Ductile to brittle transition temperature (unirradiated and irradiated)

The measured value of the ductile to brittle transition temperature (DBTT) in body-centered cubic materials depends on numerous experimental parameters, including the specimen geometry, strain rate, and the sharpness of the notch where the crack is initiated (notch acuity). The DBTT in unirradiated T-111 has generally been estimated from reduction in area measurements on un-notched tensile specimens [5,13]. The resultant DBTT value (~-200˚C) is a severe underestimate of the value which would be obtained on machined or precracked Charpy vee-notch (CVN) specimens or precracked compact tension (fracture toughness) specimens. There are no known DBTT studies on irradiated T-111, although a significant increase in the DBTT would be expected for irradiation at temperatures up to at least 650˚C, based on the large increase in hardening [6] associated with these relatively low irradiation temperatures (<0.3 T_M).

11. Recommended reference operating temperature limits

Several forced-flow corrosion and engineering loop studies have demonstrated that T-111 has good compatibility with liquid lithium at least up to temperatures of ~1370˚C [14-17]. Ta alloys have also exhibited good compatibility with other liquid metals at elevated temperatures, including Na, K and Pb to ~1200˚C [14-17]. Thermal creep becomes significant in T-111 at temperatures above ~1200˚C (~0.45 T_M), which is near the maximum temperature that corrosion data are available. Therefore, 1200˚C is selected as the tentative maximum operating temperature for Ta-base alloys such as T-111. Additional work on irradiated specimens is needed before the minimum operating temperature limit can be established. The reference minimum operating temperature limit will likely be controlled by radiation hardening, which causes loss of ductility and an increase in the ductile to brittle transition temperature. There are no known DBTT data on irradiated T-111 alloys. For the purposes of the APEX design study, the proposed reference minimum operating temperature for T-111 is 650˚C (~0.3 T_M) based on expectations of low-temperature radiation embrittlement.

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