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Sigma phase formation in irradiated tungsten, tantalum and molybdenum in a fusion power plant

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Abstract

After five years in a fusion power plant, neutrons will have transmuted a plasma-facing tungsten component into an alloy of about 75 W, 13 Os and 12 Re (atomic percent), a composition close to the homogeneous σ field of the phase diagram. Since the σ phase is extremely brittle, it is important to know whether the transformation will occur. To avoid this problem, the use of tantalum or molybdenum, as alternatives, is proposed.

1. Introduction

Tungsten is a favoured material for the plasma-facing surfaces of fusion power plants, mainly because of its high melting point and resistance to sputtering by low-energy light ions. However, under prolonged irradiation by 14 MeV fusion neutrons, under conditions expected in a fusion power plant, it will transmute significantly to osmium, via rhenium. Concern has been expressed regarding changes to the mechanical properties of W–Os–Re alloys [1], in particular to irradiation-induced hardening and embrittlement and the observation of σ phase and χ phase precipitates [2]. In the transformation from pure tungsten, α(bcc) → σ, the complex crystal structure of the 30-atom unit cell σ phase lacks slip planes and directions and so is extremely brittle. In order to assess the onset of these effects, we have calculated the compositional changes of tungsten in a typical fusion power plant first-wall.

2. The transmutation of tungsten

To quantify the transmutation evolution of a pure tungsten plasma-facing material first wall armour, we have used data from the European Power Plant Conceptual Study (PPCS) [3]. The four PPCS models (A, B, C and D) are based on a range of extrapolation in plasma physics beginning with a very limited extrapolation and ending, in model D, with a substantial advance in plasma performance. For present purposes, we have based our calculation on the fusion performance of model B power plant, a helium-cooled advanced design but based on a near-term (EUROFER) first wall material and with tungsten armour in the divertor. The average neutron wall loading is expected to be 2.0 MW m^{-2}, a figure typical of modern designs. The transmutation characteristics of a tungsten first wall armour, based on the calculated neutron spectrum in the model B design and using FISPACT-2003 data [4], are shown in Fig. 1.

Assuming a service life of 1800 days (≈5 yr) for such components, the end-of-life composition of initially pure W is expected to be (atomic percentage): W 75.1; Os 12.8; Re 11.9, plus small amounts of other elements.

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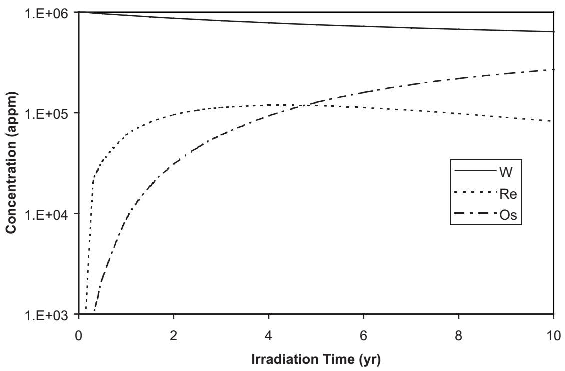

Fig. 1. Tungsten transmutation characteristics, for PPCS model B conditions.

This places the alloy composition close to the thermodynamic phase field where the crystal structure is expected to convert completely to the extremely brittle σ phase: α(bcc) → σ.

The binary phase diagrams [5] show that the α/(α + σ) boundary at 1500 °C occurs at about 94% W, for W–Os; and at about 72% W for W–Re. Similarly, the (α + σ)/σ boundary occurs at about 79% W (W–Os) and 56% W (W–Re). As shown in Fig. 2, where a linear interpolation across the ternary field is assumed, the duplex α + σ field is expected to be entered in about 2.3 years of service and the pure σ field in about 5.7 years. Hence the five year service irradiation is expected to carry the W–Os–Re composition close to the 100% σ phase field. It follows

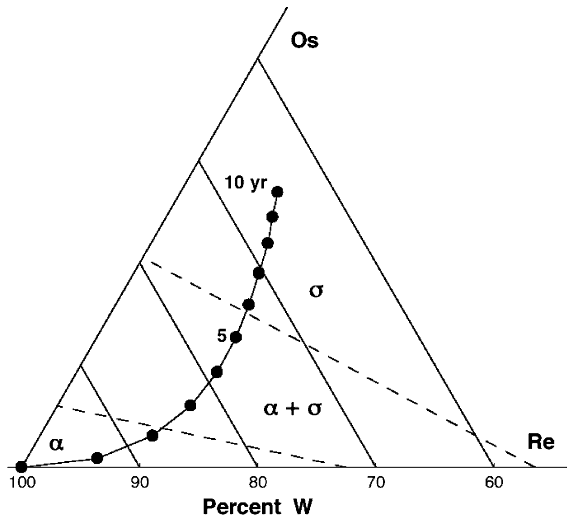

Fig. 2. The path of composition change due to 14 MeV neutron irradiation of tungsten with a wall loading of 2 MW m^{-2}. The times, in years, at which points on this path are reached, are indicated. The ternary field boundaries are interpolated from the binary phase equilibria at 1500 °C.

that in the later stages of this irradiation, little segregation by atomic migration is required to bring local compositions into this field. The only factors which might then inhibit the conversion, from the bcc crystal structure (α) of the initial W to α, are the local shuffles of the alloy atoms into their new positions; and any nucleation difficulty opposing the formation of the complex σ crystal structure.

The expected operating temperature,1000 K, of the main fusion chamber wall of a power plant is a relatively modest one for thermally activated processes in W ($\simeq 0.27T_m$) and such alloys, although a vacancy should be able to make at least 1000 jumps per second under these conditions. However, the required atomic shuffle processes are likely to be helped considerably by the local bond-loosening effects of the non-thermal vacancies created by the radiation. It is thus likely that, when the composition change makes sigma the thermodynamically favoured phase, the change to sigma will in fact occur.

3. Behaviour in a power plant

The shrinkage associated with the conversion of a bcc lattice structure to the more densely packed σ one, together with thermal shrinkage and other strains, will produce high tensile stresses in the σ phase, so that this extremely brittle material is expected to suffer extensive cracking, perhaps crumbling to powder. If it occurred, this drastic failure would seem to rule out the use of tungsten as a plasma-facing material in a power plant (unless a favourable isotope is isolated and used). Tungsten would still be usable in ITER since the lifetime fluence of neutrons is much smaller in this device. A calculation similar to the above suggests in fact that the end-of-life composition (initially 100% W) in ITER would be ≃ 98% W, ≃2% Re and 0.03% Os.

4. Tantalum and molybdenum

Tantalum is considered here as an alternative first wall material to tungsten. Its transmutation characteristics under irradiation by 14 MeV neutrons (Fig. 3) show that five years service at a 2.0 MW m^{-2} neutron wall load should generate the alloy 22.9% Ta, 76.5% W, 0.16% Os, 0.34% Re with traces of other elements. This predominantly W-based composition is well inside the single-phase BCC (i.e. primary W solid solution) field at all temperatures at which the atoms are thermally mobile, so that no σ phase is expected to form. It will be seen from Fig. 3 that the reaction Ta → W occurs rapidly, so that half of the Ta is converted to W within the first 2.5 years of irradiation, and there is only a small production of Re and Os. The use of tantalum instead of tungsten for the plasma-facing surfaces of fusion

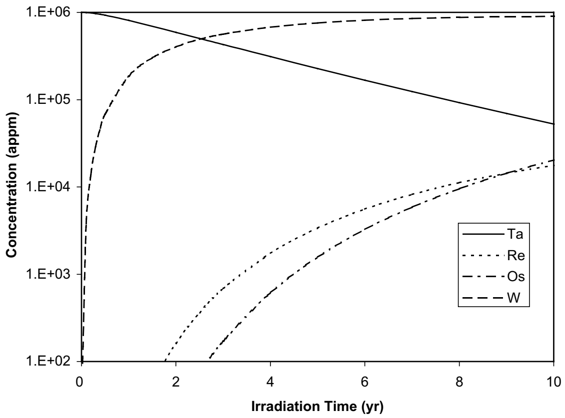

Fig. 3. Tantalum transmutation characteristics, for PPCS model B conditions.

reactors is thus expected to solve the problem of σ phase formation.

Molybdenum is also considered here as a further alternative first wall material, to avoid sigma phase formation. The same irradiation as above would produce in it 1.1% Tc and 0.65% Ru after 5 years; and 1.6% and 1.8%, respectively, after 10 years. These concentrations are well inside the primary Mo phase field at 1500 °C, the limits of which are at 28% Tc and 14% Ru, in the two binary systems.

5. Conclusion

Under neutron irradiation for five years in a fusion power plant, initially pure tungsten in a plasma-facing wall will transmute into W–Os–Re alloy with a composition near the sigma field of the phase diagram. It is likely that the initially bcc (α) structure of the material will transform to the σ phase, via atomic shuffle processes, assisted by the bond-loosening effects of the irradiation produced knock-on vacancies. This extremely brittle σ phase would be expected to lead to a fracture of the armour. The use of tantalum or molybdenum for the armour, in place of tungsten, would avoid this problem.

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