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Investigations on tungsten heavy alloys for use as plasma facing material

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HIGHLIGHTS

- Measurement of magnetisation and thermal conductivity of W–Ni/Fe heavy alloys (D185, HPM1850).
- Successful high heat flux testing of W heavy alloys with power densities of up to 20 MW/m^3.
- Exposure of W-heavy alloys in the divertor of ASDEX Upgrade in discharges with up 26 MW of heating power.

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ABSTRACT

An alternative solution for tungsten as a plasma facing material could be the use of W heavy alloys as they are produced commercially by several companies. They consist of up to 97% W and Ni/Fe (or Ni/Cu) admixtures, they are readily machinable and considerably cheaper than bulk tungsten. Their major drawbacks in view of the application in fusion experiments are the rather low melting temperature and their magnetic properties (in case of a Ni/Fe binder phase). In a first step W heavy alloys from two manufacturers were investigated concerning their thermal and magnetic properties and subjected to screening tests and cyclic loading in the high heat flux test facility GLADIS with up to 20 MW m^{-2} and surface temperatures of up to 2200 °C, showing no macroscopic failure. SEM investigations show a segregation of Ni and Fe at the top surface after the thermal overloading, but no signs of micro-cracking. The long-term behaviour of a W–Ni/Fe tile under plasma and electromagnetic load was investigated in ASDEX Upgrade using its divertor manipulator. The tile was exposed in discharges with record values of injected energy and power. Despite the observed surface modifications (Ni/Fe segregation) the W heavy alloys seem to provide a pragmatic and cost-effective alternative to bulk W tiles in the divertor of ASDEX Upgrade.

1. Introduction

Since 2014 ASDEX Upgrade (AUG) is using bulk tungsten (W) tiles at the outer divertor strike-point. In two experimental campaigns more than 2000 plasma discharges with up to 10 s duration and 100 MJ plasma heating were successfully conducted, without impairment by the W tiles. However, inspections after the campaigns revealed that a large number of tiles suffered from deep cracking attributed to brittle fracture [1]. A possible option – at least for non-nuclear fusion devices – could be the use of more ductile W heavy alloys as they are produced commercially by several companies. It consists of up to 97% (weight) W and Ni/Fe (or Ni/Cu) admixtures. According to [2,3], the endurance limits of the W heavy alloys should be considerably larger than that of W (see for example [4]) which should help to avoid cracks under the cyclic load. Their major drawbacks, in view of the application in fusion experiments, are the rather low melting temperature (≈1500 °C or <1100 °C, respectively) and the higher vapour pressure of the binder phase and their magnetic properties (in the case of Ni/Fe admixture).

In order to explore their feasibility, W heavy alloys from two suppliers (Plansee Composite Materials GmbH and HC Starck Hermsdorf GmbH) were investigated concerning their thermal and

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Table 1
Names, suppliers, composition and density of the tungsten heavy alloys under investigation.

Name	Supplier	W (wt.%)	Ni (wt.%)	Fe (wt.%)	Cu (wt.%)	Density ($g\,cm^{-3}$)
D185	Plansee	97	2.0	1.0	0.0	18.5
HPM1850	HC Starck	97	2.0	1.0	0.0	18.5
IT180	Plansee	95	3.5	0.0	1.5	18.0
HPM1801	HC Starck	95	3.5	0.0	1.5	18.0

magnetic properties and subjected to screening tests and cyclic loading in the high heat flux test facility GLADIS. In order to gain first experience under cyclic plasma load and to compare its behaviour to the divertor tiles made of bulk tungsten, one tungsten heavy alloy tile was exposed with the divertor manipulator in high power AUG discharges.

In Section 2 the measured properties (magnetic, thermal and surface composition) of the investigated materials will be presented. Section 3 presents the results of high heat flux screening and cycling loading including metallographic investigations, whereas Section 4 reports on the behaviour observed in divertor of AUG. Section 5 concludes the paper and provides the outlook on further activities.

2. Properties of tungsten heavy alloys

Tungsten heavy alloys are compounds with a large fraction of tungsten and admixtures of either Ni/Fe or Ni/Cu produced by pressing and sintering of powders or liquid phase sintering. Several commercial suppliers offer various grades of these W heavy alloys and they are widely used as shielding material and balancing weight because of the high atomic number (shielding) and high density (shielding, balancing). Table 1 summarizes the names, suppliers, composition and density of the tungsten heavy alloys under investigation. In respect to tungsten these alloys are considerably cheaper due to the facilitated sintering process and they show improved machinability and ductility at room temperature. The latter points could provide essential advantages when being used as plasma facing material in present day fusion devices because of the many thermal cycles they are undergoing due to the pulsed operation and the cyclic loading through ELMs. The downside of the material is, of course, the low melting point of the alloying elements Fe, Ni and Cu being 1538 °C, 1455 °C and 1085 °C, respectively, which considerable restricts the operational space. However, when trying to avoid recrystallisation of tungsten to preserve its original mechanical properties the temperature should be kept anyway below 1300 °C, which means that the use of Fe and Ni should not affect the operation too strongly. Other issues to be taken into account when using W heavy alloys are their magnetic properties and their thermal conductivity.

Fig. 1 shows a typical scanning electron (SEM) image of a DENSIMET D185 surface in its initial (as machined) state. Nickel (as well as iron) can be identified at the boundaries of large grains as demonstrated on the right side of the figure which is obtained by

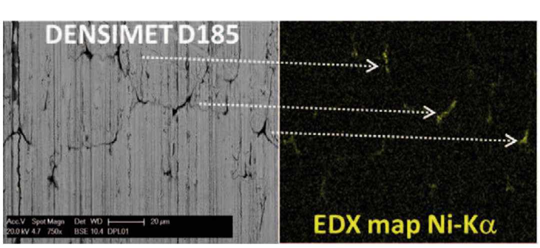

Fig. 1. SEM image and EDX map of the DENSIMET D185 surface (machined, as received).

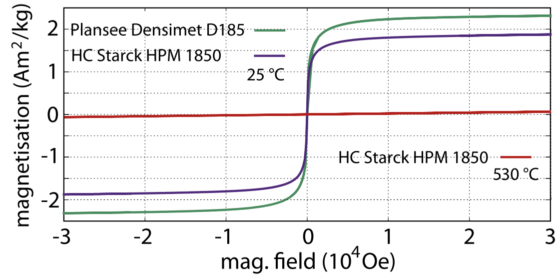

Fig. 2. Magnetisation of HPM1850 and D185 as a function of magnetic field at 25 °C and 530 °C (HPM1850 only).

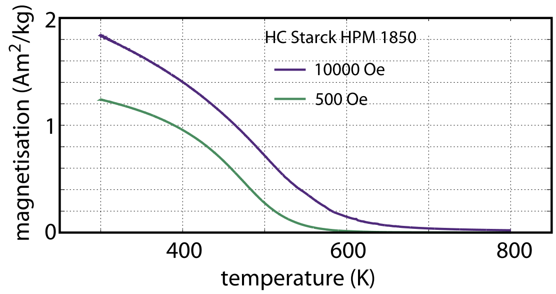

Fig. 3. Magnetisation of HPM1850 as a function of temperature.

mapping of the characteristic x-ray emission by energy dispersive x-ray spectroscopy (EDX).

As stated above, it is important to know the detailed magnetic properties when using materials inside a fusion device because of the potential perturbation of the local magnetic field as well as the forces and moments the tiles will experience. Therefore the magnetisation was measured up to a magnetic field of 3×10^4 Oe ($\simeq$3 T vacuum field) at room temperature (see top of Fig. 2) for D185 and HPM1850 and at temperatures up to 530 °C (HPM1850 only, Figs. 2 and 3). The magnetisation saturates very quickly with increasing magnetic field at very moderate levels (the magnetisation of Eurofer, which is also tested in AUG (see [5]) is a hundred times larger).

The magnetisation of D185 is about 20% higher than that of HPM1850, which might be explained by a slightly higher Fe content in D185 (the specification comprises 1.0 ± 0.3 weight % Fe). HPM1850 loses its ferromagnetism above $T \approx 330$ °C which hints to the fact that in this case the magnetic properties are dominated by Ni.

The thermal diffusivity was measured by the laser flash method using a laser flash apparatus (NETZSCH, LFA 427) in the range from 50 °C up to 1200 °C (laser: Nd:Cr:GGG, wave length 1064 nm, detector: InSb, atmosphere: Ar flux 190 ml/min). The thermal conductivity was determined by multiplying the thermal diffusivity with density and specific heat. The temperature dependent data of specific heat of pure Fe, Ni, and W are taken from [7] combining them linearly according to their fractional mass. The density (18.5 $g\,cm^{-3}$) was assumed to be approximately constant. The thermal conductivity of D185 and HPM1850 is very similar, irrespectively whether the material has been overloaded (see Section 3) or it is in its initial state (the differences in the measurements at a certain temperature are within the estimated error). Interestingly the thermal conductivity slightly increased from about 80 $W(mK)^{-1}$ at 50 °C up to 95 $W(mK)^{-1}$ at 1200 °C. As a consequence, the thermal response of the surface of a HHF loaded component is very similar as for bulk tungsten although at room temperature the thermal conductivity of W is almost twice (see also Section 3.)