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HiperFer, a reduced activation ferritic steel tested for nuclear fusion applications

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ABSTRACT

Materials are the most urgent issue in nuclear fusion research. Besides tungsten, steels are considered for unifying functional and structural materials due to their cost and mechanical advantages over tungsten. However, the fusion neutrons impose a strong constraint on the ingredients of the steel in order to avoid long lasting activation, while the material has to pertain sputtering resistance, low hydrogen retention, and long-term mechanical stability. In this proof-of-principle, we demonstrate the interesting properties of the new material HiperFer (High performance Ferrite) as a material suitable for fusion applications.

The investigation covers neutron activation modelled by FISPACT-II, plasma sputtering and deuterium retention experiments in PSI-2, thermo-mechanical properties and component modelling. The material was found to feature a low nuclear inventory. Its sputtering yield reduces due to preferential sputtering by a factor 4 over the PSI-2 D_2 plasma exposure with possible reductions of up to 70 indicated by SD.Trim.SP5 modelling. The exposure temperature shows a strong influence on this reduction due to metal diffusion, affecting layers of 1 µm in PSI-2 at 1150 K exposure for 4 h. Deuterium retention in the ppm range was found under all conditions, together with ~10 ppm C and N solubility of the ferritic material. The creep and cyclic fatigue resistance exceed the values of Eu-97 steel. As an all HiperFer component, heat loads in the order of 1.5 MW/m^2 could be tolerated using water-cooled monoblocks. In conclusion, the material solves several contradictions present with alternative reduced-activation steels, but its applications temperatures >820 K also introduce new engineering challenges.

1. Introduction

Plasma-facing-materials were, so far, selected according to plasma physics requirements, leading to special materials with high purity such as Be or W. In future reactors engineering issues will become more important than plasma physics, introducing a paradigm shift in material selection. Therefore, materials with excellent engineering (strength, ductility, fatigue life) and processing properties (welding, casting) will be required, but still keeping their plasma properties, nuclear activation, and product cost in mind.

Steels naturally provide a good compromise in this space of qualities. Several types were already developed for nuclear fusion applications with Eu-97 [1] being one of the most prominent types. Since the development of Eu-97 steel research in fusion and other fields revealed several weaknesses and relevant improvements, leading to e.g. the so-called generation 3 and 4 ferritic-martensitic steels [2]. The HiperFer steel [3] originally intended for highly efficient and dynamic conventional power plants is in line with several ideas of these new developments and beyond. HiperFer is a ferritic steel requiring five functional ingredients (Fe, Cr, Si, W, and Nb or Ta) which are acceptable from a nuclear activation point of view. The material is strengthened by intermetallic Laves phases (typically AB_2), giving the material good high-temperature creep strength and mechanical fatigue strength. At the same time, the high W content for the Laves phases in the order of 3–6 wt% offers the prospect of good plasma sputtering resistance. The high Cr content suffices to allow for hot-steam oxidation resistance as passive safety mechanism in a loss of coolant event.

This study aims at evaluating HiperFer for use in a nuclear fusion environment. Samples from two casts of the material with 18–21 at.% Cr, 0.8–1.2 at.% W, 0.5% Si, and 0.5 at.% Nb were available for testing. The study includes plasma exposures in PSI-2 [4], thermo-mechanical data, compositional analysis, hydrogen retention, thermal and nuclear modelling. The comparison with W and other steels allows judging the relative performance of HiperFer. Finally perspectives for further optimization of the material towards nuclear fusion applications and future experiments will be given.

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Table 1
Composition of HiperFer W4 analysed by ICP-OES and LECO CS/TCH 600 with uncertainties < 10%.

Weight %	Fe	Cr	Nb	Si	Mn	Co	Ni	W	C	S	N	O
HiperFerW4	75.1	16.5	1.0	0.3	0.186	0.0067	0.0081	4.2	0.002	0.001	0.004	0.005

2. Material aspects

The HiperFer steel was produced specifically for testing by casting in batches of 80 kg. CroFer®22H and W reference materials were commercially produced. The used W material produced by Plansee has a purity of 99.994% and corresponds to ITER specifications. It is identical to W materials used in all fusion experiments at Forschungszentrum Jülich. HiperFer was not specifically heat-treated (i.e. it entered the relevant tests without strengthening Laves phase particles), prior to the experiments, neither were the other materials thermally modified. All samples were polished on the plasma-exposed surfaces using diamond suspensions to a roughness of $R_a \approx 12$ nm.

The HiperFer with 4 wt% W (HiperFerW4) was analysed by inductively coupled plasma with optical emission spectroscopy for its metallic composition down to the 10 ppm detection limit of the applied device. The composition is depicted in Table 1. C, N, O, S were analysed by LECO CS/TCH 600 analysers (infrared absorption of outgassing). The magnetic properties of the steel were not quantitatively characterized, but a clear ferromagnetic behaviour, similar to Eu-97, was present. Tests revealed a good adhesion of HiperFer-HiperFer diffusion welding bonds starting from 920 K. Also connections with W, e.g. as additional armour are possible and under investigation. As the material can be cast and welded, complex geometries and manufacturing are in general unproblematic and low overall cost can be expected for a reactor construction.

HiperFer features several specific strength for applications above 820 K. At temperatures above 950 K, the mechanical parameters significantly deteriorate, but a non-structural operation remains possible at least up to 1150 K, as demonstrated below. At temperatures in the range of 600–820 K, reversible structural changes slowly embrittle the steel, requiring at least regular heating above 840 K for recovery. HiperFer's Cr content leads to two orders of magnitude lower high-temperature steam oxidation rates compared to 9% ferritic-martensitic steels (see “18Cr” alloy vs. P92 in [3]) such as Eu-97, making it suitable for supercritical-steam based power plants. The application of HiperFer therefore suggests coolant temperatures of 820–950 K, leading to about twice the thermal to electric conversion efficiency compared to ~550 K coolant temperature concepts for fusion reactors. Especially in nuclear environments, where Nickel based alloys are not applicable, HiperFer might be the only available structural reduced-activation material applicable for this exceptional conversion efficiency. Additionally, not being dependent on carbides makes it potentially more stable in hydrogen environments such as nuclear fusion. On the other hand, > 820 K introduces new engineering challenges for a reactor design and the use of liquid metals might be difficult at these high temperatures. Tolerable power load densities on plasma-facing components could also be lower due to the limited temperature difference of about 300 K. In contrast to fission reactors, where the water coolant temperatures are limited to the sub-critical range due to the direct contact to the fuel elements, fusion reactors offer a high degree of flexibility in selecting (supercritical) coolant temperatures, allowing for this improved economics and radiation resistance.

The engineering properties such as tensile properties, fatigue lifetime, and creep are discussed in separate papers [5,3]. In general, HiperFer has exceptional engineering parameters and lifetime under cyclic loads at high temperatures. In comparison to non-Laves phase steels the values are significantly improved. For example, the creep rupture strength improves by a factor of up to two (Fig. 1). Furthermore, the thermal expansion is about 10% smaller compared to T92, which is similar to Eu-97, as depicted in Fig. 2.

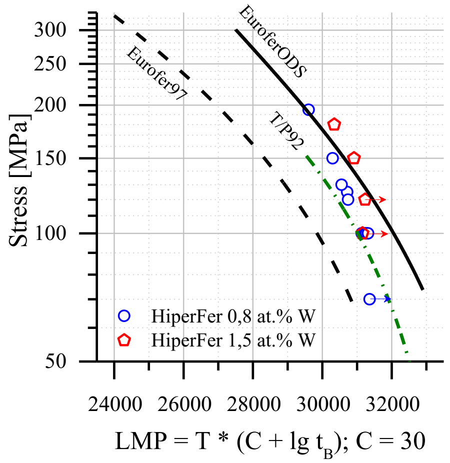

Fig. 1. Creep rupture strength analysis with comparison to other steels. The data were generalised by the Larson–Miller relation with a constant of C = 30 to the Larson-Miller parameter (LMP). Arrows indicate ongoing experiments. Eurofer97 data were taken from [1], EuroferODS from [6], and T/P92 data from [7].

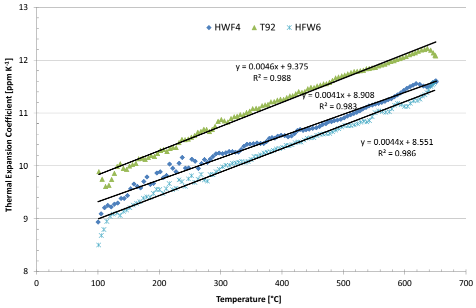

Fig. 2. Thermal expansion measured for both HiperFer variants and T92 (similar to Eu-97) from 370 K to 925 K. Linear fits and resulting parameters next to each dataset. The expansion clearly reduces with higher W content of the steel.

3. Nuclear properties

Low neutron activation is a decisive factor for qualification of fusion reactor materials. Use of MCNP6 [8] calculated neutron flux as input into FISPACT-II [9], an inventory calculation program, is the present norm for activation prediction of reactor materials. Fluxes corresponding to a 1.6 GW fusion power DEMO reactor were obtained from work performed in [10] and inserted as a 709 energy group into FISPACT-II. Using TENDL-2015 [11], computations were performed for the activation of HiperFer with Nb and Ta alloying, Eu-97, pure W, and pure Fe similar to the calculations presented in [12]. A 30% availability of DEMO was considered using proportionally reduced average neutron flux over 2 years, in line to the start-up blanket forecast [13] for reasons of comparability to literature. For the steels, measured impurity concentrations were considered in the calculations. HiperFer-Nb and HiperFer-Ta were assumed to feature the same composition, except for a 1:1 atomic substitution of Nb for Ta. The results shown in Fig. 3 exhibit relevant differences between the steels and Fe only after 10 years of cooling. After 10 years, Fe features the lowest activity, closely followed by HiperFer-Ta. Eu-97 remains on a 10 times and HipferFer-Nb on a