

# Low Activated Materials as Plasma Facing Components

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**Abstract.** Low activated materials such as ferritic steel, vanadium alloy and SiC/SiC composite have to be developed for realization of a fusion demonstration reactor. Major issues concerning these low activated materials have been evaluation of neutron irradiation effects and feasibility as blanket materials. Since these are also in-vessel materials, issues of plasma material interactions have to be investigated. Ferritic steel, F82H, is well oxidized in the atmosphere. Thus, pre-baking is necessary before installation. The required baking temperature is higher than 900 K. Vanadium alloy, V-4Cr-4Ti, absorbs hydrogen well and hydrogen embrittlement takes place when the hydrogen concentration exceeds a critical level. In order to avoid hydrogen absorption, the formation of an oxide layer on the alloy was found to be very useful. In JFT-2M, the vanadium alloy was exposed to a deuterium discharge environment for 9 months. On the alloy surface, an oxide deposition layer with a thickness of 200 nm was formed. The deuterium concentration observed was very low, only 1.3 wppm. SiC/SiC composite may be employed as divertor plates in addition to its use as blanket material. Fuel hydrogen retention was very similar to that of graphite but the chemical erosion was negligibly small.

## 1. Introduction

In order to realize a fusion demonstration reactor, it is very important to develop low activated structure materials with a long lifetime. In the case of ITER, an austenitic stainless steel such as 316LSS can be used since the neutron fluence estimated is only  $0.3 \text{ MWa/m}^2$  which corresponds to 3 dpa. The neutron fluence in the demonstration reactor exceeds 10-15  $\text{MWa/m}^2$  (100-150 dpa), and the material data under such a high level of irradiation are not yet available. Three materials, ferritic steel such as F82H, vanadium alloy V-4Cr-4Ti, and SiC/SiC composite, have been regarded as candidate low activated materials [1-3].

The major issues discussed so far are to evaluate whether these materials can be used under a neutron fluence higher than 100-150 dpa and to investigate their adaptability with coolant as blanket material. However, these materials are employed as in-vessel components such as first wall of blanket, divertor wall and vacuum chamber. Thus, the issues of plasma material interactions have to be investigated in order to clarify the suitability of these materials as plasma facing components [1]. In the following, the gas desorption properties of ferritic steel, F82H, the hydrogen absorption properties of vanadium alloy, V-4Cr-4Ti, and the hydrogen retention of SiC/SiC composite are described.

## 2. Gas Desorption Properties of Ferritic Steel

The ductile-brittle transition temperature, DBTT, of F82H saturates at relatively low neutron fluence, 10 dpa, and the temperature is 473 K [2]. Thus, this material can be used at a temperature higher than 473 K. Adaptability with pressurized water coolant is good. In order to achieve high mechanical strength at a temperature higher than 873 K, oxide dispersion strengthened (ODS) ferritic steel has to be developed. In addition, neutron damage at fluence higher than 100 dpa and the effect of helium produced by nuclear reactions have to be clarified.

The nickel concentration of the ferritic steel is very low and the oxygen diffusion speed in this material is higher compared with austenitic steel, so that oxidation easily occurs. Since the ferritic

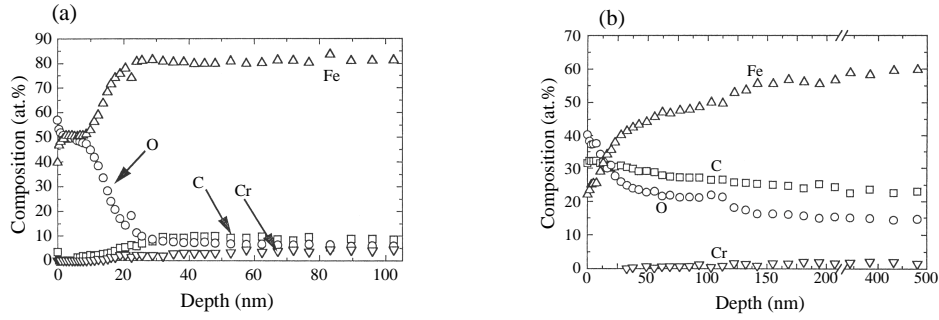


FIG.1. Depth profiles of F82H as supplied by the manufacture (a) and F82H exposed to the atmosphere for 2 years (b).

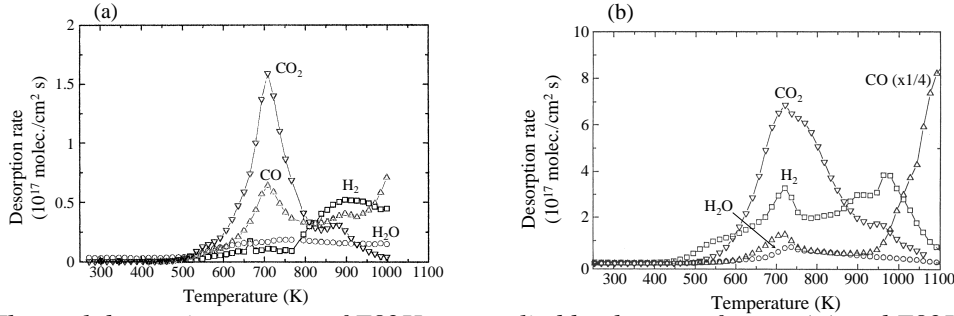


FIG.2. Thermal desorption spectra of F82H as supplied by the manufacture (a) and F82H exposed to the atmosphere for 2 years (b).

steel is used in the vacuum chamber and in-vessel components, surface impurity and gas desorption have to be examined before installation. Figure 1 shows the depth profiles of atomic composition for F82H as supplied by the manufacture (a) and F82H exposed to the atmosphere for 2 years (b), which were obtained by AES. The oxide layer of F82H was 20 nm, which is comparable to that of austenitic steel. However, the oxide layer was expanded to several hundred nm after 2 years exposure. In addition, the carbon concentration increased. For these materials, the gas desorption spectra were taken by TDS. The sample was placed in vacuum and then resistively heated. During the heating, the desorbed gas species and the desorption rate were quantitatively measured by QMS. Figure 2 shows the gas desorption spectra for F82H as supplied by the manufacture (a) and F82H exposed to the atmosphere for 2 years (b). Major outgassing species were  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$  and  $\text{H}_2$ . The total gas desorption amount of FIG. 2(a) was comparable to that of austenitic steel. However, the gas desorption became extremely large after exposure to the atmosphere for 2 years. The total desorption amount was one order of magnitude larger compared with the case before the exposure. In particular, the desorptions of  $\text{CO}$  and  $\text{CO}_2$  are dominant. In addition, the fraction of gas species containing oxygen relative to total outgassing was approximately 90%. Thus, pre-baking before installation is necessary and the required temperature is higher than approximately 900 K.

### 3. Hydrogen Absorption of Vanadium Alloy

The mechanical strength of vanadium alloy is high and operation at high coolant temperature is possible. Thus, high energy conversion efficiency can be expected [2]. Lithium has been considered as a coolant in vanadium alloy blanket. Since the vanadium alloy is employed with liquid metal coolant, the installation coating on this alloy has to be developed.

Even if the operation temperature is high in the vanadium alloy blanket, this material is exposed to fuel hydrogen environment. Since the hydrogen absorption amount is very high at low temperature, the major concern is hydrogen embrittlement, which occurs when the hydrogen concentration exceeds 400-1000 wppm. Thus, the hydrogen absorption properties have to be

investigated for the design of a vanadium alloy blanket. Figure 3 shows the hydrogen absorption amount versus the absorption temperature for an absorption time of 1 h at 10 Pa. These data were taken by thermal desorption after the exposure of vanadium alloy to a hydrogen gas environment. When the temperature was higher than 800 K, the absorption saturated within 1 h. However, the absorption did not saturate within 1 h for temperature below 800 K. If the absorption time is longer, the absorption amount is shown by the broken curve of FIG. 3. Thus, embrittlement takes place.

It is known that an oxide layer can reduce the diffusion of hydrogen. So, the vanadium alloy was exposed to an oxygen gas environment at various temperatures. After the exposure, the vanadium alloy with an oxide layer with different thickness was fabricated. The formation of titanium oxide in the surface layer was observed by XPS. The surface oxidized alloy was again exposed to a hydrogen gas environment, and the absorption amount was measured. Figure 4 shows the hydrogen absorption amount for the vanadium alloy with an oxide layer with different thickness. When the oxidation temperature was higher than approximately 700 K, the thickness of the oxide layer decreased by oxygen diffusion into the bulk. When the oxidation temperature was lower than approximately 600 K, a thick oxide layer was formed. The thickness was larger than 200 nm. In the case with a thick oxide layer, the hydrogen absorption amount was one or two orders of magnitude reduced compared to the case with non-oxidation or with a thin oxide layer. Thus, surface oxidation is useful to avoid hydrogen absorption. If Ti-O coating is made and the coating is stable, the lifetime of vanadium alloy determined by hydrogen embrittlement is greatly lengthened.

In JFT-2M, vanadium alloy (V-4Cr-4Ti) samples were placed on a 304SS holder and exposed to a deuterium discharge environment for 9 months [4]. The position was behind the baffle plate, so that the sample was exposed to mainly neutral deuterium atoms and molecules. When a divertor discharge was conducted, the temperature of samples and holder was 573 K. The total shot number of divertor discharge was 200 during 9 months period. The shot length and the pressure during the discharge were 1 s and 0.1-0.2 Pa, respectively. After the extraction of the vanadium alloy samples and the SS holder, the depth profiles of the vanadium alloy and the 304SS were analyzed by AES. Figure 5 shows the depth profiles of vanadium alloy (a) and 304SS (b). In both cases, a deposition layer with thickness of 200-400 nm was observed. From the point of view of thermal stability of compounds, it can be conceived that titanium oxide was formed. Thermal desorption spectra for vanadium alloy and 304SS are shown in FIG. 6 (a) and (b), respectively. The implanted deuterium was desorbed in the form of HD and D<sub>2</sub>. The deuterium concentrations of vanadium alloy and 304SS were 1.3 wppm and 0.04 wppm, respectively. The retained amount was very small even in the case of vanadium alloy. It is presumed that an oxide layer with a thickness of 200 nm might have suppressed the deuterium diffusion into the bulk.

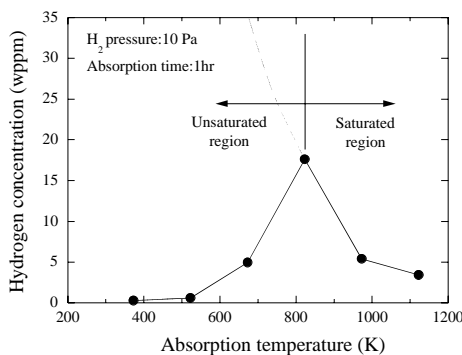


FIG.3. Hydrogen absorption amount versus absorption temperature for an absorption time of 1 h and hydrogen gas pressure of 10 Pa.

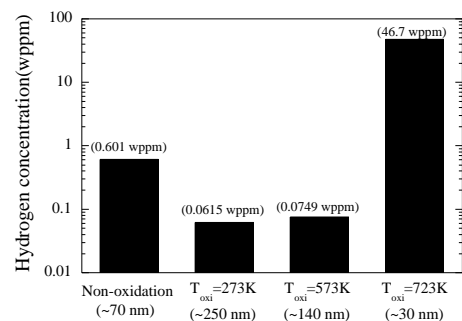


FIG.4. Hydrogen absorption amounts for oxidized vanadium alloy with different oxide thicknesses.

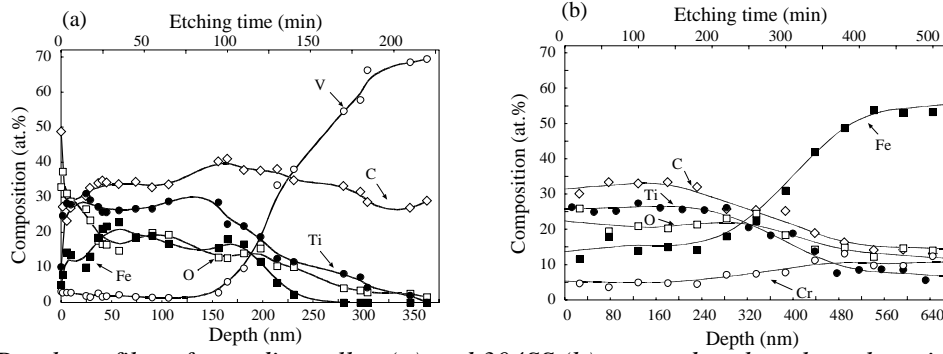


FIG.5. Depth profiles of vanadium alloy (a) and 304SS (b) exposed to the tokamak environment of JFT-2M.

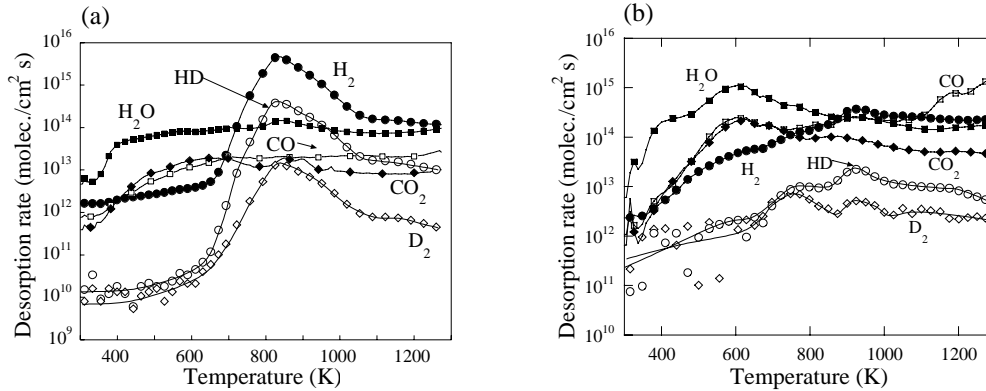
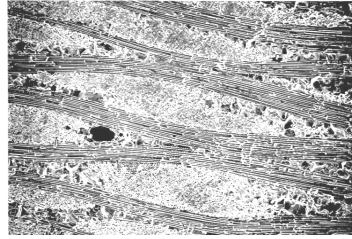


FIG.6. Thermal desorption spectra of vanadium alloy (a) and 304SS (b) exposed to the tokamak environment of JFT-2M.

#### 4. Deuterium Retention of SiC/SiC Composite

Activation of SiC/SiC composite is the lowest among these three materials if the impurity is well reduced. In addition, the operation temperature can be high in the blanket of this material. Even at high temperature, the mechanical strength is still high [2]. Since this material is porous, the coating has to be developed to avoid gas permeation. The data on neutron irradiation are quite poor.

SiC/SiC composite has a high fracture toughness. Thus, it is attractive to employ this material as divertor plates. In this case, major concerns are fuel hydrogen retention and chemical erosion. The SiC/SiC composite has a surface morphology as shown in FIG. 7. The material consists of SiC fibers and SiC binders. In the manufacturing process, the carbon content at the fiber surface was relatively high. Deuterium ion irradiation was conducted on this material. After that, deuterium retention and chemical erosion were examined by thermal desorption. Figure 8 shows the thermal desorption spectrum for the case of a deuterium fluence of  $2 \times 10^{18}$  D/cm<sup>2</sup>. The peak temperature of D<sub>2</sub> desorption was 1073 K, which is very similar to graphite. However, CD<sub>4</sub> desorption was negligibly small. In the case of graphite, the fraction of implanted deuterium desorbed in form of CD<sub>4</sub> is approximately 10%. Figure 9 shows the deuterium retention versus deuterium ion fluence. The retained amount was very similar to that of graphite. The use of SiC/SiC composite has an advantage with respect to chemical erosion.



400 μm

FIG.7. Photograph of SiC/SiC composite taken by scanning electron microscope, SEM.

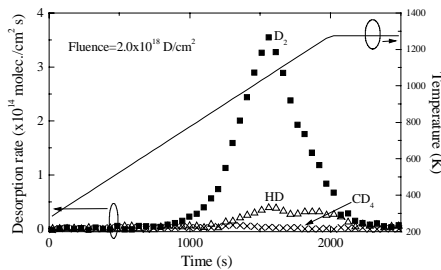


FIG.8. Thermal desorption spectrum of SiC/SiC composite after deuterium ion irradiation with a fluence of  $2 \times 10^{18} \text{ D/cm}^2$  at RT.

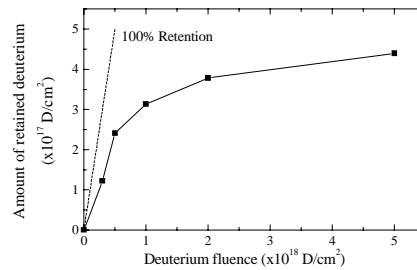


FIG.9. Amount of retained deuterium in SiC/SiC composite versus deuterium ion fluence.

## 5. Summary

Ferritic steel is easily oxidized in the atmosphere. The gas desorption of oxidized ferritic steel was very large, one order of magnitude larger than that before the exposure. Thus, pre-baking before installation has to be conducted. The required temperature becomes higher than 900 K.

Vanadium alloy absorbs hydrogen very well, and thus the concern is hydrogen embrittlement. Hydrogen absorption experiments have been carried out by changing the parameters such as temperature and thickness of surface oxide layer. When the titanium oxide layer exceeded 200 nm, the hydrogen absorption was remarkably reduced. Thus, lifetime of the vanadium alloy can be lengthened by the titanium-oxide coating. In JFT-2M, the vanadium alloy was exposed to the tokamak environment for 9 months. The oxide layer was formed on this material due to the deposition of impurities and titanium by titanium flush. The retained amount of deuterium was only 1.3 wppm, much lower than the critical concentration, 400-1000 wppm. It is conceived that the oxide layer might have suppressed deuterium diffusion into the bulk.

When SiC/SiC composite is employed as divertor plates, fuel hydrogen retention and chemical erosion have to be examined. The fuel hydrogen retention was very similar to that of graphite. However, the chemical erosion was observed to be negligibly small.

## References

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