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Overview of Indian activities on fusion reactor materials

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ABSTRACT

This paper on overview of Indian activities on fusion reactor materials describes in brief the efforts India has made to develop materials for the first wall of a tokamak, its blanket and superconducting magnet coils.

Through a systematic and scientific approach, India has developed and commercially produced reduced activation ferritic/martensitic (RAFM) steel that is comparable to Eurofer 97. Powder of low activation ferritic/martensitic oxide dispersion strengthened steel with characteristics desired for its application in the first wall of a tokamak has been produced on the laboratory scale. V–4Cr–4Ti alloy was also prepared in the laboratory, and kinetics of hydrogen absorption in this was investigated. Cu–1 wt%Cr–0.1 wt%Zr – an alloy meant for use as heat transfer elements for hypervapotrons and heat sink for the first wall – was developed and characterized in detail for its aging behavior. The role of addition of a small quantity of Zr in its improved fatigue performance was delineated, and its diffusion bonding with both W and stainless steel was achieved using Ni as an interlayer. The alloy was produced in large quantities and used for manufacturing both the heat transfer elements and components for the International Thermonuclear Experimental Reactor (ITER).

India has proposed to install and test a lead–lithium cooled ceramic breeder test blanket module (LLCB-TBM) at ITER. To meet this objective, efforts have been made to produce and characterize Li_2TiO_3 pebbles, and also improve the thermal conductivity of packed beds of these pebbles. Liquid metal loops have been set up and corrosion behavior of RAFM steel in flowing Pb–Li eutectic has been studied in the presence as well as absence of magnetic fields. To prevent permeation of tritium and reduce the magneto-hydro-dynamic drag, processes have been developed for coating alumina on RAFM steel. Apart from these activities, different approaches being attempted to make the U-shaped first wall of the TBM box are briefly described.

India has also initiated the development of fusion grade superconductors. Success achieved in the fabrication of Nb_3Sn based multi-filamentary wires using the internal tin process and cable-in-conduit-conductors is also briefly presented.

1. Introduction

Recognizing the potential of thermonuclear fusion in meeting the rapidly increasing demand of clean energy, India launched a fusion research program by establishing the Institute of Plasma Research at Gandhinagar, Ahmedabad. The Institute, a constituent unit of the Department of Atomic Energy, has already a working tokamak, *Aditya*, which is being used for '*Plasma Physics*' research. A Steady State Tokamak-1 (SST-1) with a superconducting magnet system has recently been commissioned. The first plasma in this was struck in June, 2013 with a superconducting magnet system. The indigenous program envisages further development in terms of making a SST-2 by 2027, followed by a DEMO by 2037, and finally a fusion power reactor by 2050. Further, in the year 2005, India joined as an equal partner in the International Thermonuclear Experimental Reactor (ITER) program, in which the commitment of the country lies in delivering a large inventory of sophisticated components (Fig. 1). Also, India was allotted half-a-port for placing our Lead–Lithium cooled Ceramic Breeder (LLCB) Test Blanket Module (TBM) in ITER, the primary objectives of placing this TBM in ITER being to test its capability to (i) breed tritium with Tritium Breeding Ratio (TBR) > 1, and to (ii) extract the high grade heat from the tokamak with acceptable thermal efficiency.

2. Materials for tokamak

Tokamak is a device that is based on the concept of magnetic confinement of plasma in which a mixture of D and T is burned to obtain the energy. The fusion reaction that takes place may be

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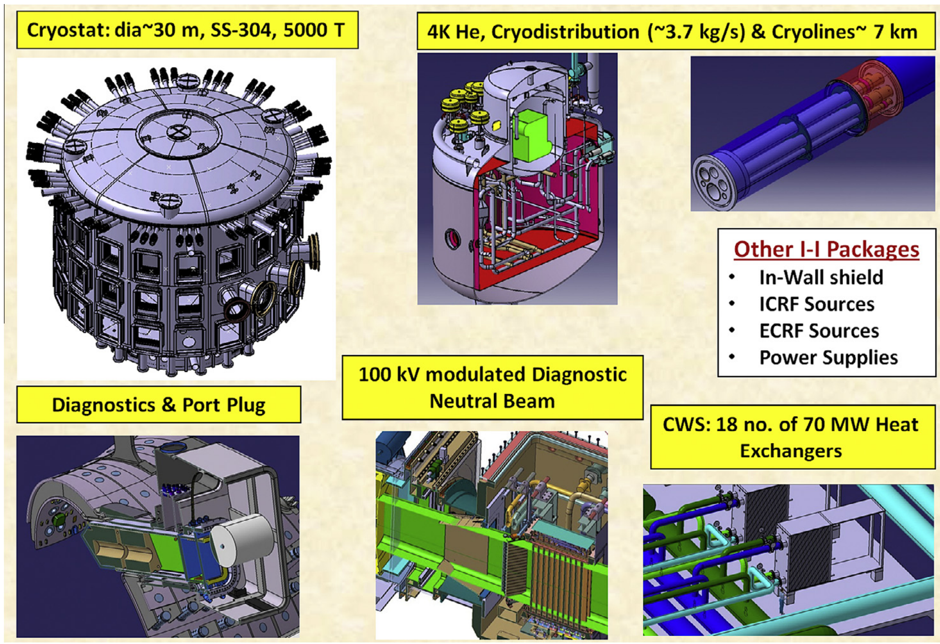

Fig. 1. Supplies committed to ITER by India.

written as: D + T = ^{4}He (3.5 MeV) + *n* (14.1 MeV). General descriptions of tokamaks and the demanding service conditions of structural and functional materials in a tokamak are given in several excellent reviews, Refs. [1–4] being only a few selected ones from them. Table 1 summarizes the candidate materials now being considered for applications in the first wall of a tokamak.

2.1. First wall structurals

2.1.1. Steels

2.1.1.1. Development of India specific reduced activation ferritic/martensitic (RAFM) steel. The development of Indian RAFM steel was executed [5–14] systematically and scientifically by adopting three stages of development; (i) pilot scale melting and physical and mechanical properties evaluation of an internationally established RAFM steel, (ii) establishing the specifications of Indian RAFM steel through melting of several laboratory scale heats of RAFM steel with different chemical compositions and detailed characterization of their mechanical properties, and (iii) commercial scale development.

In the pilot scale development phase, three heats having composition of Eurofer 97, each weighing around 200 kg, were melted at Mishra Dhatu Nigam Limited (MIDHANI). Strict control was exercised on the radioactive tramp elements (Mo, Nb, B, Cu, Ni, Al, Co, Ti) and on the elements that promote embrittlement (S, P, As, Sb, Sn, Zr, O). Based on the variation of prior austenite grain size and hardness of the steel with temperature and time, the optimum normalizing and tempering heat treatment conditions of the steel were arrived at as 1253 K for 30 min and 1033 K for 60 min, respectively. The microstructure of the furnace cooled steel, which consists of a mixture of ferrite (α) and martensite ($\acute{\alpha}$) is shown in Fig. 2(a). The normalized and tempered steel had a tempered martensitic microstructure with coarse $M_{23}C_6$ carbides, rich in Cr and W on the lath boundary and fine intralath Ta and V rich MX precipitates (Fig. 2(b) and (c)). The ductile-to-brittle transition temperature (DBTT) estimated on the basis of 68 joule criterion was below 203 K, as reported for Eurofer 97. The variations of 0.2% offset yield strength and ultimate tensile strength with test temperature were comparable to those of Eurofer 97. Creep properties of the pilot scale RAFM steel studied in air over a wide stress range at 773, 823 and 873 K, showed creep rupture strength comparable to Eurofer 97 steel. Low cycle fatigue strength was found to be slightly lower than Eurofer 97 but within the scatter band.

In the second phase of development, four heats of the steel were melted with tungsten and tantalum contents in the ranges 1–2 wt% and 0.06–0.14 wt%, respectively. The steels were subjected to normalization (1250 K for 30 min) and tempering (1033 K for 90 min) heat treatments, which produced a tempered martensitic microstructure. The high temperature phase stability of the steels was studied by calorimetric measurements and the transformation temperatures were determined. The critical cooling rate for $\gamma \rightarrow \acute{\alpha}$ formation was determined as a function of austenitizing temperature and time, to generate the continuous cooling transformation (CCT) plots. The thermodynamic properties such as relative enthalpy and specific heat were measured by a combination of drop and differential scanning calorimetry. Increase in tungsten content increased the ductile-to-brittle transition temperature (DBTT), low cycle fatigue and creep strength of the steel, whereas the tensile strength was not changed significantly. Increase in tantalum content increased the DBTT and low cycle fatigue strength of the steel whereas the tensile and creep strength decreased. Detailed TEM investigations revealed enhanced microstructural stability of the steel against creep exposure on tungsten addition.

Table 1
Materials for the first wall of a tokamak.

First wall plasma facing
- Low Z – Be, C–C composites
- High Z – W, Mo-based alloys

First wall heat sink
- Cu–Cr–Zr alloy
- Copper alloys dispersion strengthened by alumina

First wall structural
- Steels
  - Low activation austenitic steels [SS 316L(N) IG] for the first wall of ITER
  - Ferritic/martensitic steels (F82H, EUROFER) for the DEMO and the TBMs
  - Nanostructured ferritic/martensitic ODS steels for the PROTOTYPE
- Vanadium alloys
- SiC-fiber/SiC composites