DEVELOPMENT OF HEAVY LIQUID METAL TECHNOLOGY FOR FUSION REACTOR TECHNOLOGY FOR FUSION REACTOR MATERIAL CHARACTERIZATION

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Introduction

One of the challenges in developing suitable structural materials for fusion reactor (ITER and DEMO) is to make sure that they are compatible with the heavy meals and alloys which have been proposed as potential coolants. India has proposed Lead–Lithium eutectic (Pb$_{83}$Li$_{17}$) cooled Ceramic Breeder (LLCB) as the blanket concept for testing at ITER. The LLCB blanket concept proposes Pb$_{83}$Li$_{17}$ eutectic as neutron multiplier, secondary tritium breeder, and coolant for the CB zones [1-2]. In the initial stages, a number of structural materials, including various classes of stainless steels, SiC/SiC and vanadium based alloy (V-5Cr-5Ti) had been considered for the construction of TBM. The best suited material will be chosen by considering its thermo-mechanical properties, capability to withstand high neutron flux and most importantly compatibility with the coolant. Lead lithium eutectic (Pb$_{83}$Li$_{17}$), has been found to be highly corrosive to most of the structural materials where the corrosion is mostly due to dissolution of the constituent elements and not due to chemical reaction. [3]. Thus, the extent of dissolution of constituent elements from the proposed containment materials will be the critical factor in choosing the best candidate for fusion reactor structural. BARC took up this challenge and successfully created and commissioned elaborate experimental facilities for development of heavy liquid metal technology. Quick and significant progress has been achieved in the materials front in a short time and foremost among these is the development of certain key aspects of liquid metal technology. Liquid metal technology development in the context of Indian TBM for ITER is one of the principal group efforts in the Fusion Reactor Materials Section (FRMS), BARC.

Liquid Metal Test Facilities

Liquid Metal loops

FRMS already had expertise to handle liquid metals like lead-bismuth eutectic for the ADS project and had operated liquid metal buoyancy loops for extended periods of up to 10,000 h. With the ITER project in hand, the above experience was used to develop liquid metal technology related to lead-lithium eutectic. Initially, buoyancy driven lead-lithium loops were designed and fabricated. The hot leg and the cold leg temperatures were maintained at 500°C and 400°C respectively. The loops were operated for 1000 h by keeping samples of 9Cr-1Mo (P91) material inside for corrosion studies. The exposed 9Cr-1Mo samples were characterised fully and the corrosion phenomenon was studied in detail [4].
After successful operation of two such loops, a pump driven (forced circulation) lead-lithium loop was designed which demanded indigenous development of liquid metal based components like electromagnetic pumps, heat exchangers and flow meters. The electromagnetic pump comprised of a SS316L channel having a wall thickness of 1 mm and a rectangular cross section. The overall channel diameter was 300 mm and the thickness of liquid metal contained by it was 8 mm. The channel was housed between two rotating discs where Samarium–Cobalt magnets were placed on the discs with pairs facing each other. The electrically conductive fluid (Pb$_{83}$Li$_{17}$) between these magnetic pairs was moved by a Lorentz force generated by rotating of the magnets. The magnitude of pressure developed is given by equation (i).

\[ P_{\text{max}} = 0.5 \times \sigma \times V_b \times B^2 \times S \times L_{ch} \times K \]  

Where \( B \) is the magnetic field (T), \( \sigma \) is the electrical conductivity of the liquid (S.m\(^{-1}\)), \( V_b \) is the velocity of the magnetic field (m/s); \( L_{ch} \) is the length of the active part of pump channel (m), \( S \) is the slip and \( K \) is the coefficient accounting for transversal end effects. The average flux between poles of the opposite magnets was 0.42 T and the maximum pressure developed by the pump at a speed of 1400 RPM was 4 bars. The maximum discharge obtained till date has been 60 l/m.

All components were fabricated and a pump driven loop was operated on lead-lithium eutectic for 1000 h continuously keeping P91 samples inside. The temperature of test section was kept at 550°C while the temperature of heat exchanger was at 350°C. At a rotation speed of 650 RPM from the electromagnetic pump a liquid metal flow rate of 30 l/m was obtained.
Recently, a 1.8T electromagnet has been procured and a pump driven liquid metal loop based on lead-bismuth eutectic was developed with the electromagnet attached over the corrosion test section. After successful operation of this loop for 1000 h, a similar loop with lead-lithium eutectic is being now fabricated for corrosion testing of P91 in the presence of magnetic field.

**Rotating Disc Test facility**

Velocity of liquid metal flow is an important factor affecting is corrosion behaviour at a particular temperature. To study the effect of different flow velocities on the corrosion behaviour of Pb$_{83}$Li$_{17}$ on structural materials, rotating disc experiments been planned at FRMS. For this purpose a magnetic coupling based rotating disc reactor has been indigenously designed and fabricated in house and has been successfully commissioned. The initial experiment was carried out to study the compatibility of P91 material at 550°C in Pb$_{83}$Li$_{17}$ at a rotation speed of 1200 RPM for 2000 hrs. An improvised rotating disc type test facility was designed to study the compatibility of Indian Reduced Activation Ferritic Martensitic Steel (IN-RAFMS) with Pb$_{83}$Li$_{17}$ eutectic and experiment has been completed by exposing an IN RAFMS disc to Pb$_{83}$Li$_{17}$ at 550°C for 3000 h.

**Static test facilities**

A number of static test facilities have been designed for studying the compatibility of structural materials with Pb$_{83}$Li$_{17}$ under various conditions of temperature and material history. The corrosion behavior of Fe9Cr1Mo steel samples in a static Pb$_{83}$Li$_{17}$ eutectic melt at 823K was analyzed in an especially designed necked quartz capsule [5]. The samples were kept isothermally for 2000 h. The changes in microstructure and depletion of alloying components of the samples were studied using scanning electron microscope (SEM), energy disperses X-Rays (EDS) and electron probe beam microanalysis (EPMA). Weight loss and thinning of the walls were calculated by gravimetric analysis method. Using these data the change in thickness per year was calculated.

**Compatibility of Fusion Reactor Structural Materials**

**Corrosion of SS316L in Pb$_{83}$Li$_{17}$**

The Corrosion mechanism of SS316L in flowing Pb$_{83}$Li$_{17}$ has been interpreted in detail based on the data obtained from buoyancy driven loop and static experiments. It has been observed among all the alloying elements, nickel has the highest affinity to dissolve into Pb$_{83}$Li$_{17}$ and thereby is the main factor responsible for the formation of a porous ferritic layer on the exposed surface of the steel facing Pb$_{83}$Li$_{17}$ [6]. The effect of oxygen ingress in Pb$_{83}$Li$_{17}$ loop has also been analyzed thoroughly [7]. Novel techniques to reduce the corrosion rate of SS316L through introduction of nickel and oxygen in Pb$_{83}$Li$_{17}$ have been investigated upon and satisfactory results have been obtained.

**Fig 4:- Rotating disc Corrosion test facility**

**Fig 5: Corroded layer on the surface of SS316L exposed to Pb$_{83}$Li$_{17}$ at 500°C for 1000 h**
The corrosion mechanism and corrosion rate of P91 at 500°C in flowing Pb83Li17 has been established based on the data obtained from buoyancy and pump driven loops [4]. It has been observed that P91 is more resistant to corrosion than SS316L primarily because of the negligible quantity of nickel present in P91. The deposition of corrosion products in the cooler regions of the loops have been analysed and the deposition rate of chromium has been found to be higher than nickel 400°C. The corrosion rate of P91 disc exposed to Pb83Li17 at 550°C in the rotating disc test facility after 2000 h has been found to be 0.119 mm/yr at a flow velocity of 700 RPM. It has been observed that the presence of magnetic field enhances the corrosion rate by 2-3 times of the initial value and the interaction of this magnetic field with the flowing liquid metal results in localized corrosion leading to formation of evenly spaced surface irregularities [8].

The effect of magnetic field of the corrosion behavior of INRAFMS will be studied in a unique set up where the movement of liquid metal would be controlled by a rotating magnetic field. The fabrication of such a set up has been started and the data generated would add to the earlier database and help in understanding the corrosion mechanism of ferritic martensitic steel exposed to Pb83Li17 under magnetic field at the operating temperature of ITER.

Acknowledgements

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References

5. S. Kumar and N. Krishnamurthy, Fusion Engineering and Design; 2012; doi 10.1016/j.fusengdes.2012.01.014

Recent Developments

A unique experimental set up has been designed and fabricated to test the creep behavior of structural steels in the presence of Pb83Li17, at a high temperature and under a uni-axial tensile load. The stress on the sample is indirectly applied through pressurizing of bellows which are connected to the sample but placed above the level of molten eutectic. The displacement of sample along with time/temperature is measured by an LVDT connected to the sample but isolated from the bellows. The first experiment has been started in this set up with a 170 mm long IN- RAFMS creep sample exposed to Pb83Li17 at 823 K and under a uniaxial tensile load of 200 MPa.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Corrosion rate at 500°C after 1000 h (μg/cm².h)</th>
<th>Deposition rate at 400°C after 1000 h (μg/cm².h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9Cr-1Mo (10mmx 40mmx2mm)</td>
<td>17.4</td>
<td>1.25</td>
</tr>
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</table>

Table 1: Corrosion and Deposition rate of P91 samples obtained from buoyancy loop.