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Behavior of liquid Li-Sn alloy as plasma facing material on ISTTOK

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ABSTRACT

The high power loads impinging on the first wall and particularly the divertor of fusion reactors is a decisive factor to the success of nuclear fusion. An alternative to solid plasma facing components is the use of liquid metals such as lithium or tin due to the regenerative properties of the liquid surface. Another suitable candidate is the eutectic lithium tin alloy (30 at.% Li) which is suggested to display beneficial properties of both its constituent elements. The application of these materials as liquid metal plasma facing components depends on several factors such as their affinity to retain hydrogenic isotopes and the discharge performance degradation induced by the enhanced impurity contamination, among others. An experimental setup has been developed to produce and expose samples to ISTTOK plasmas on both liquid and solid states. Samples of Li-Sn alloy were exposed at ISTTOK to deuterium plasmas. Post-mortem analysis of the samples was performed by means of ion beam diagnostics. To quantify the fuel retention on the samples the nuclear reaction analysis (NRA) technique was applied. Complementary, Rutherford backscattering spectrometry (RBS) was used for determination material composition, particularly of impurities, on the samples. Regardless of the high sensitivity of these techniques no deuterium was detected in the samples. Emission of the Li-I 670.7 nm line indicates that there was interaction of the plasma with the samples. Alternative reasons for the low retention of this material are discussed. Lithium segregation to the surface of the sample was observed.

1. Introduction

One of the unsolved issues in nuclear fusion is related to the high power loads impinging on the first wall particularly on the divertor region of the reactor. Using liquid metals, such as lithium, gallium or tin as plasma-facing material has been pointed out as possible alternative to the solid walls option due to the regenerative properties of the liquid surface. However, the use of these materials in fusion reactors depends on the discharge performance degradation induced by the enhanced impurity contamination and on their affinity to retain hydrogenic isotopes, among other factors.

Extensive work on lithium exists in the literature [1–3] and it has been claimed that the maximum wall temperature is limited by its high evaporation rate. Less is known for gallium and tin however some studies on gallium's behavior under tokamak conditions were made previously at ISTTOK [4,5] and work is currently being performed on tin. Nonetheless, the high atomic number of these two materials, particularly for tin, is seen as a disadvantage.

Alternatively, the combination of tin and lithium in an alloy (Sn with 20–30 at.% Li) displays beneficial properties, which also qualify it as a suitable candidate. The evaporation rate of this material is at least three orders of magnitude lower than that of pure lithium while keeping an effective charge similar to lithium's [6].

The aim of this work was to evaluate the deuterium content in the alloy samples (both solid and liquid) for different total integrated exposure times. For this the samples were irradiated under several half second AC discharges within ISTTOK edge plasma. To that purpose an experimental setup was developed to monitor the samples production. Similar plasma conditions and fixed radial positions were used for each individual irradiations. Deuterium retention measurements were achieved by means of ion beam analysis.

2. Experimental setup

For the purpose of exposing the liquid metal samples two different setups were developed: (i) a positioning and conditioning

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system and (ii) a controlled preparation chamber for the samples. These two are built upon the previous systems described in earlier work with gallium [5].

2.1. Sample preparation

The Li-Sn alloy used in this work was produced by alloying pure Li and Sn metals under vacuum at the Nuclear Radiations Laboratory at the U. Illinois Urbana. Its composition was chosen to be 30 at.% of lithium and 70 at.% tin ($Li_{30}Sn_{70}$).

The preparation chamber, is used to monitor each sample's first fusion under UHV conditions similar to those in the tokamak vessel. A method was developed to prepare the samples in which the samples are loaded inside this chamber using the same holding cup as the one that will be later introduced in the tokamak. Then the current on the heater is raised until the surface temperature of the sample is above its melting point at which point it is kept constant until the sample is uniformly melted and the pressure becomes stable. During this stage it is common to observe a migration of most impurities (namely oxides) to the liquid metal surface. In these situations the chamber's horizontal manipulator is used to wipe out the surface. Since there is no capillary porous system keeping the liquid metal in the holder it is important to assure a good wetting on the holder's cup. Since tin is commonly used as a welding material its wetability is naturally assured. However it is still necessary to have the stainless steel substrate cleaned in hydrochloric acid followed by an ultrasonic bath. After this preparation the samples and the bottom part of the manipulator are quickly transferred to the tokamak.

Once the sample holder is installed in the tokamak vessel and properly degassed, it is raised to its final exposure position and reheated. The surface temperature of the samples was monitored using a pyrometer (optris CTlaser 3ML) focused on the sample from the top connector of the port. Restricted due to the limited access to the bottom of the tokamak the same two stage system implemented previously in [5] was used. The positioning system consists of a set of bellows whose compression is imposed via the manual fastening of a threaded shaft thus allowing for vertical motion. The upper bellow is used for coarse positioning of the sample beyond the vessel limits while the bottom allows a fine adjustment. A cross-section of this system is depicted in Fig. 1 attached to the tokamak vessel. A gate valve is placed between the tokamak chamber and positioning system to allow vacuum separation of the regions. Along this system is a structural rod where the sample holder is fixated and to which additional wires can be attached to carry current to the sample holder. The sample holder is made of a bulk piece of boron nitride with a threaded nichorome filament that serves as heating element. Around this there is an electrically isolated stainless steel shield which protects the filament and on top is a substrate cup which holds the sample material.

2.2. Sample exposure in ISTTOK

The tokamak ISTTOK is a high aspect ratio device with a circular cross-section whose main parameters are: $R = 46$ cm, $a = 8.5$ cm, $B_T = 0.5$ T, $I_p = 5$ kA. In the recent years ISTTOK has been operated in AC-mode [7] which consists of several alternated pulses per discharge. This operation extended the discharge time to the range of seconds due to improvements in the real-time control system [8,9] which in turn allows for a quicker production of samples. The typical parameters for ISTTOK's edge plasmas are: electron and ion, $T_e \sim T_i = 30$–40 eV, electron density, $n_e = 0.5$–3×10^{18} m^{-3}, particle flux $\Gamma^{D+} = 1$–7×10^{22}/m^{2}s and discharge duration of 250 ms (each shot consists of ten alternating pulses with a duration of ~25 ms).

All the liquid metal samples were exposed at a normalized radial position of $r/a = 0.8$, heated above their respective melting points and irradiated in the liquid state under deuterium plasmas. Another sample was positioned at the same equivalent position in the solid state allowing for a comparison between induced effects caused by solid and liquid exposures. After being exposed to the plasma the samples were allowed to solidify and then removed from the tokamak to open air conditions.

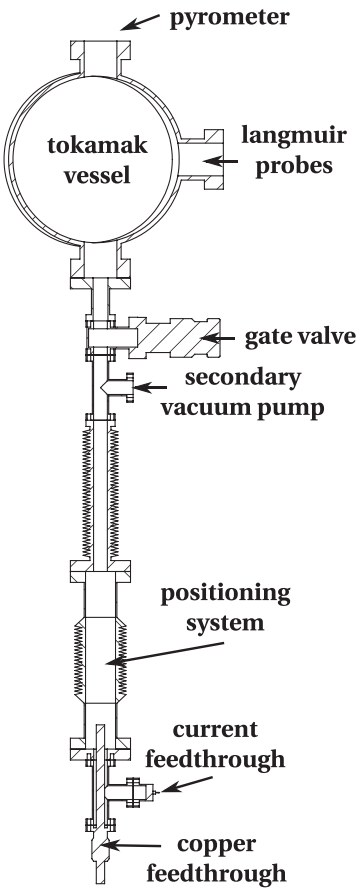

Fig. 1. Sample positioning and conditioning system coupled to the ISTTOK vessel.

Fig. 2. Tin sample in its holder after exposure to ISTTOK plasmas.

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