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Chamber wall materials response to pulsed ions at power-plant level fluences ☆,☆☆

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Abstract

Candidate dry-wall materials for the reactor chambers of future laser-driven Inertial Fusion Energy (IFE) power plants have been exposed to ion pulses from RHEPP-1, located at Sandia National Laboratories. These pulses simulate the MeV-level ion pulses with fluences of up to 20 J/cm^2 that can be expected to impinge on the first wall of such future plants. Various forms of tungsten and tungsten alloy were subjected to up to 1600 pulses, usually while being heated to 600 °C. Other metals were exposed as well. Thresholds for roughening and material removal, and evolution of surface morphology were measured and compared with code predictions for materials response. Powder-metallurgy (PM) tungsten is observed to undergo surface roughening and subsurface crack formation that evolves over hundreds of pulses, and which can occur both below and above the melt threshold. This roughening is worse than for other metals, and worse than for either tungsten alloyed with rhenium (W25Re), or for CVD and single-crystal forms of tungsten. Carbon, particularly the form used in composite material, appears to suffer material loss well below its sublimation point. Some engineered materials were also investigated. It appears that some modification to PM tungsten is required for its successful use in a reactor environment.

1. Introduction

The first wall of an Inertial Fusion Energy (IFE) power plant will be subjected to intense pulsed neutrons, X-rays, and energetic ions produced from explosions of fusion material at the reactor chamber center. An experimental investigation is underway at Sandia National Laboratories of the effects of these ion and X-ray pulses on candidate chamber dry-wall materials. The energetic ions are produced by the RHEPP-1 facility, and the X-rays by the *Z*

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facility. Materials exposure results from Z are discussed elsewhere in this issue. We report here on the exposure of first-wall armor materials to intense ion beams. The RHEPP-1 (Repetitive High Energy Pulsed Power) accelerator was used to produce fluences of either helium or nitrogen ions of up to 10 J/cm^2 per pulse, with ion energies as high as 1.8 MeV (for doubly charged nitrogen). The repetitive capability of RHEPP-1 resulted in sample exposure to many ion pulses, as many as 1600 per sample investigated. The ion current pulsewidth varied from 150 ns to nearly 500 ns. As discussed in the paper by Sethian et al. in this issue, this time is shorter than the debris ion arrival time, but comparable to the fusion product arrival time expected in future reactors. Accordingly, the fluence thresholds discussed below may be lower than what might be expected for an actual reactor, as the diffusion into the substrate occurring with longer pulsed energy delivery times mitigates the surface heating effect.

A future laser IFE reactor may be operated at a pulse rate as high as 10 Hz. This amounts to an annual total of 3×10^8 pulses to the first wall. Besides the considerable thermal energy delivered to the wall surface on each pulse, there likely will be effects of a thermomechanical nature caused by the pulsed energy delivery, such as expansion of the near-surface region against the (relatively) unheated subsurface, fatigue responses, etc. Ions with up to 20 J/cm^2 fluences and several MeV energies will impinge normal to and penetrate well below the surface (1–10 μm). Surface sputtering can be secondary to ablation/sublimation of the wall surface. To ensure survivability, effectively no erosion of the flat wall surface per pulse can be tolerated (<1 nm/pulse). In addition to high melting/vaporization points, additional durability can be expected from materials with good ductility, fatigue response, and high thermal conductivity. 'Engineered' materials, e.g. with non-flat geometry, may also be constructed in a way to better distribute the heat load and mechanical stresses.

Initially, the investigative emphasis was on determining the threshold for both surface ablation, and surface roughening, as shown in Fig. 1. Sample exposure consisted of multiple single-pulse events, on the order of 50 or 75. For example, the roughening threshold measured for powder-metallurgy tungsten (PM W) [1] at room temperature (RT) was determined by monitoring the reflected light from an initially smooth surface with a laser reflectometer at increasing fluence per pulse. Using the nitrogen beam from RHEPP-1, the received signal was observed to remain constant until a level of 1.25 J/cm^2 was reached. At this level, each subsequent pulse produced a progressive reduction in received signal from the previous pulse. This indicates that the laser light was increasingly scattered by the roughening surface. The total number of pulses in this case was 53. In another experiment, the ablation threshold for unheated PM W was determined to be about 6 J/cm^2, by monitoring the step height produced at the boundary of exposed and unexposed surface, using a 1-D profilometer. This value is consistent with predictions from both the BUCKY [2] and SIM [3] modeling codes.

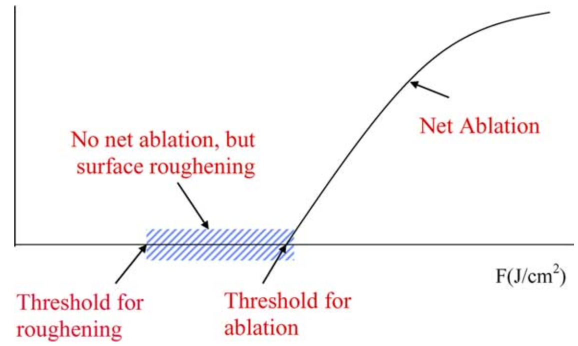

Fig. 1. Schematic of plan for investigation of surface roughening and ablation.

The next step then was to determine if the exposed sample would remain unaffected by repeated exposures below the measured thresholds. The number of exposures was greatly increased [4]. It was found that for unheated PM W exposed to 400 pulses (nitrogen), an exposure below the 1.25 J/cm^2 fluence threshold resulted in no increase to surface roughness, whereas above this value, the level of roughening (measured by the roughness parameter R_a) increased dramatically with beam fluence. For other materials, such as the carbon matrix portion of carbon fiber composite (CFC), it is unclear whether there is a lower fluence limit below which the sample remains unaffected (see discussion below). More significantly, however, it became clear from such studies that the materials response to large numbers of ion pulses can become quite complex, and can take hundreds of pulses to evolve. The effects appear to have various causes, such as thermomechanical and fatigue response in the case of PM W, or possibly physical sputtering or radiation-enhanced sublimation in the case of the CFC matrix material.