CONF-750905--21

SURFACE EROSION OF FUSION REACTOR COMPONENTS DUE TO RADIATION BLISTERING AND NEUTRON SPUTTERING

By

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FOR PRESENTATION AT

7th European Conference on Controlled Fusion and Plasma Physics
Lausanne, Switzerland; Sept. 1-5, 1975

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

operated under contract W-31-109-Eng-38 for the
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Seventh European Conference on Controlled Fusion and Plasma Physics,
Lausanne, Switzerland, 1-5 September 1975

SURFACE EROSION OF FUSION REACTOR COMPONENTS DUE TO RADIATION BLISTERING AND NEUTRON SPUTTERING

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Abstract: Radiation blistering and neutron sputtering can lead to the surface erosion of fusion reactor components exposed to plasma radiations. Recent studies of methods to reduce the surface erosion caused by these processes are discussed.

Energetic plasma radiations striking the surfaces of structural components (e.g., vacuum walls, beam limiters, diverter walls) of fusion reactors can cause a variety of surface phenomena and thereby (a) release major quantities of gas which will contaminate the plasma, and (b) cause damage and erosion of the bombarded surface as reviewed earlier [1-4]. Two of the more important surface erosion and plasma contamination processes in the operation of thermonuclear fusion reactors have been identified to be radiation blistering and 14-MeV neutron sputtering [4-8]. Radiation blistering occurs when energetic projectiles from the plasma region strike the exposed surfaces of reactor components. If such projectiles penetrate through solids with sufficient energy, they displace lattice particles from their sites and are implanted in the lattice at the end of their range. In the region of intense radiation damage (i.e., near the end of the projectile range) vacancies formed can combine to form voids. If the solubility of the implanted gas is small (e.g., helium in metals) a fraction of the gas can precipitate out of solution and combine with the voids to form gas-filled bubbles. Such bubbles near the surface region can grow (e.g., by coalescence of smaller bubbles), and when the gas pressure is high enough they can plastically deform the surface skin to form visible blisters that may eventually rupture. The release of bursts of gas from ruptured blisters was first observed mass spectrometrically by Kaminsky for deuteron-bombarded copper [9]. He also observed a pitting of surface regions where blisters had exploded (using surface replica techniques in conjunction with transmission electron microscopy). The bursts of gas released by blister rupture can contaminate the plasma, and the peeling of the blister skin can result in serious wall erosion [1, 11-28]. A close relationship between the skin thickness of ruptured blisters and the projected range of the incident ions is observed [7, 11]. Recent experiments have shown that the blister size, shape, and density depend on such parameters as the diffusivity and solubility of the implanted projectiles in the target material [7, 11, 12, 28]; the projectile energy and angle of incidence (affecting the projected range of the projectile in the solid) [11-13, 19, 28]; the yield strength of the material [5, 12, 26, 29]; the target temperature [12, 20, 23, 25-28]; the dose rate [16]; the total dose [5, 7, 11, 16, 19-28]; the orientation of the crystal axes to the projectile beam [20, 21]; and the initial defect concentration in the target [5, 7]. At this time a comprehensive theory of blistering does not exist.

The significance of the helium blistering process to the surface erosion of fusion reactor components can be illustrated by some of the high blistering yield values observed. For example, the blistering yield S_b for 304 st. steel at $450^\circ C$ for 100 keV helium bombardment to a dose of 0.5 C/cm^2 ($S_b \sim 3$ atoms/ion) is nearly two orders of magnitude larger than the estimated combined sputtering yields for 25 keV D^+, T^+, and 100 keV He^+. Therefore blistering by helium projectiles in the 100-keV range can become a more effective surface erosion process than physical sputtering by deuterons, tritons and helium ions for a comparable energy range. From the erosion yield for the 304 st. steel for 100 keV He^+, a thickness loss of about 0.09 mm per year can be estimated for a helium-flux of 1×10^{13} projectiles $cm^{-2}sec^{-1}$. This value alone is rather high, and other processes such as physical and chemical sputtering, and vaporization of the blister skin due to energetic photon absorption will also contribute to the erosion rate [1-3].

One possible way to reduce surface erosion due to helium blistering in fusion reactor components is to maintain the surfaces at a high temperature (e.g., $> 900^\circ C$ for Nb and V) at which some of the implanted helium is released without forming large bubbles [3-5]. However, the operating temperatures of various components may be limited by other design criteria. Another solution suggested recently [29] is the choice of a material with a microstructure which minimizes the formation of blisters. A promising class of materials appear to be sintered metal powders with small average grain size ($\sim 0.5\ \mu m$) and preferably with low atomic number Z. An experimental study of the surface erosion due to helium blistering in aluminum and sintered aluminum powder (SAP) has been made for irradiation at room temperature with 100 keV He^+ ions to a dose of 1.0 C/cm^2. The results show a large reduction in the erosion rate in SAP by more than three orders of magnitude as compared to the erosion rate in pure aluminum [29]. Studies on sintered beryllium powders are in progress. Another promising class of materials are metals (e.g., Nb - 1%Zr alloy) coated with glasses or ceramics. Preliminary results obtained at 300°C indicate a significant reduction in helium blistering.

The experimental and theoretical information available on neutron sputtering is scarce and contradictory (for reviews see refs. 1–4, 8). The experiments by the authors were undertaken to provide information on the erosion of surfaces of monocrystalline metals, of cold rolled and annealed polycrystalline metals (e.g., Nb, V, Au), and of SiC with various surface finishes under 14-MeV neutron bombardment. The observations reveal the following results [8, 30]:

(1) The deposits of materials such as Nb, V, and SiC appear in two forms: (a) one form covered the substrate surface in an atomic form as a fractional atomic layer; (b) the other form was discovered as chunks of various sizes and irregular shapes. The emission of chunks had not been observed in ion-sputtering experiments and was not anticipated by any existing sputtering theory.

(2) Both types of deposits are not uniformily distributed over the collector area but are clustered along streaks or appear in patches. The direction of the streaks appears to be parallel to the direction of cold rolling of the sample from which the chunk has been ejected and is not related to any microstructure of the collector surface.

(3) The number of chunks, their size and shape depend very strongly on the tensile stresses in the surface regions (e.g., due to cold rolling), and on the degree of microstructure of the irradiated surface (e.g., microprotrusions, microcracks). For example, the highest chunk emission has been observed for the case of a cold rolled niobium surface with a finish of about 5 μm. In turn, no chunk emission was observed for an annealed niobium sample with a surface finish of ~ 0.1 μm and for a monocrystalline niobium sample with a surface finish of ~ 0.03 μm. These results suggest that the chunk ejection can be reduced or eliminated if the tensile stresses in near surface regions are reduced (e.g., high-vacuum anneal, monocrystalline target) and if the surface smoothness is improved. To what extent recent observations by other authors [30] of no chunk emission from cold rolled niobium foils under 14 MeV neutron bombardment can be related to differences in surface stresses and surface finishes of the samples or to differences in the detection techniques cannot be answered readily at this time. Our observations of chunk emission are well described qualitatively by a theory recently developed by Guinan [31]. Methods to reduce surface

erosion by neutron sputtering will be discussed in the presentation of this paper.

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*Work performed under the auspices of the Energy Research and Development Administration.

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