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EROSION TESTS OF MATERIALS BY ENERGETIC PARTICLE BEAMS*

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D. E. SCHECHTER, C. C. TSAI, F. SLUSS, W. R. BECRAFT,† D. J. HOFFMAN

Oak Ridge National Laboratory
P.O. Box Y, Oak Ridge, Tennessee 37831
(615) 574-1120

ABSTRACT

The internal components of magnetic fusion devices must withstand erosion from and high heat flux of energetic plasma particles. The selection of materials for the construction of these components is important to minimize contamination of the plasma. In order to study various materials' comparative resistance to erosion by energetic particles and their ability to withstand high heat flux, water-cooled copper swirl tubes coated or armored with various materials were subjected to bombardment by hydrogen and helium particle beams. Materials tested were graphite, titanium carbide (TiC), chromium, nickel, copper, silver, gold, and aluminum. Details of the experimental arrangement and methods of application or attachment of the materials to the copper swirl tubes are presented. Results including survivability and mass losses are discussed.

INTRODUCTION

A concern for present and future magnetic confinement devices is the lifetime limitation due to thermal fatigue and erosion of the internal components used for plasma heating and impurity control. These components, which include limiters, divertor collector plates, rf launchers, and Faraday shields, must handle high fluxes of energetic particles from the plasma periphery. Depending on the proximity of these components to the plasma, the average continuous heat flux could be 1000 W/cm^2, and the average particle flux could be 10^{19} particles/cm^2·s. During plasma disruptions, transient (~10-ms) heat fluxes of 10 to 100 kW/cm^2 can occur. The design study of FED/INTOR[1] determined that the development of materials and technology for the internal components is one of the critical issues of ongoing fusion research.

The selection of materials for the construction of these components is important in order to minimize contamination of the plasma and degradation of confinement for long time periods. The materials must therefore be very resistant to erosion, thermal shock, and thermal fatigue. Materials with elements having low mass numbers are also desirable. Materials presently being used or suggested include graphite, TiC, Cr, Ni, Al, and Be.

In present short-pulse (<5-s) confinement experiments, the energy lost to the internal components is handled inertially (the mass of the component absorbs the energy from one pulse, which then dissipates slowly to the surroundings by radiation and conduction between pulses). Future experiments with pulse lengths extended to tens of seconds will require active cooling (a coolant flowing through the component). During the development of neutral beam systems[2,3] in the last ten years, it was demonstrated that water-cooled copper swirl tubes could handle high (~7-kW/cm^2) heat flux. Limiters fabricated of swirl tubes have been proposed.[4] Oak Ridge National Laboratory (ORNL) has prime responsibility for the development of rf plasma heating technology for the next-generation fusion devices in the United States. The rf compatibility of materials and geometrical configurations have been and are being studied and have been reported at this meeting.[5] In addition, information about the erosion properties of materials is necessary so that functional rf launchers and Faraday shields can be developed.

Therefore, a study was initiated at ORNL to test various materials' comparative resistance to erosion by energetic particles. The materials were actively cooled by being applied or attached to copper swirl tubes. It is recognized that not only the materials themselves, but also the quality of their adhesion to the swirl tubes, were being tested. The materials tested were graphite, TiC, Cr, Ni, Cu, Ag, Au, and Al. Although copper (uncoated), silver, and gold may not be serious candidates, they were included for comparison.

An Oak Ridge Tokamak (ORMAK) injector[6] was the source of energetic particles with which to bombard the material samples. Beams of hydrogen and helium particles (ions and neutrals) were produced.

SAMPLE PREPARATION

The test samples were prepared using a copper swirl tube substrate. The swirl tubes had an outside diameter of 0.90 cm, a wall thickness of 0.16 cm, and a length of 23.5 cm with a twisted Inconel ribbon inside, as shown in Fig. 1.

All tested materials except copper (uncoated tube) were applied or attached to the copper swirl tubes by electroplat-

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†General Electric Company, Schenectady, NY 12345.

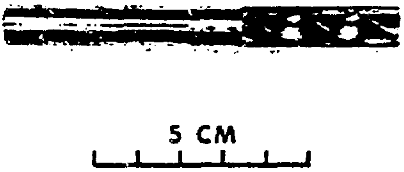

Fig. 1. Swirl tube.

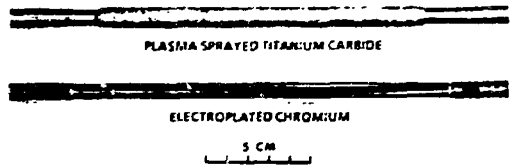

Fig. 2. Plasma-sprayed TiC (above) and electroplated Cr (below).

ing, plasma spraying,[a] and brazing. Nickel, chromium, silver, and gold were electroplated onto the tubes to a thickness of 0.13 mm for a length of ~15 cm. Titanium carbide, aluminum, nickel, and chromium were plasma sprayed to the same dimensions. See Fig. 2 for examples.

Graphite was attached to the tubes by brazing. Semicylindrical shells were machined from POCO EDM-3[b] graphite to outside radii of 0.64 cm, inside radii ~0.04 mm greater than a tube outside diameter (resultant wall thicknesses of 0.19 cm), and lengths of 2.5, 10.2, and 12.7 cm. For one version of sample, the 10.2-cm-long shell was machined with 0.5-mm-wide slits 1.3 cm apart. Other versions used one 12.7-cm-long and five 2.5-cm-long segments, respectively. The graphite shells were brazed to the copper swirl tubes with Ticusil[c] brazing alloy foil in a vacuum furnace at 850°C. See Fig. 3.

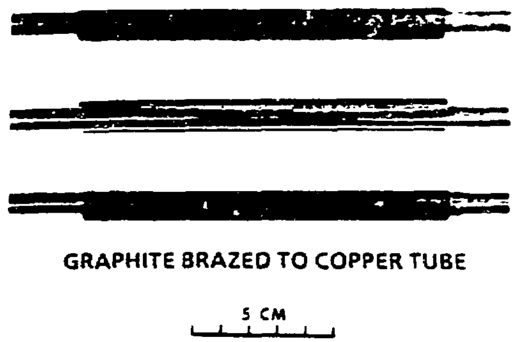

Fig. 3. Graphite test samples.

TEST ARRANGEMENT

The test arrangement is shown in Fig. 4. The particle beam was produced by an ORMAK neutral beam injector with a 10-cm duoPIGatron ion source. Beams of hydrogen and helium particles (ions and neutrals) were produced. The power density reaches a maximum in the focal plane about 108 cm downstream from the ion source. The test sample was positioned at this point normal to the axis of the beam. The power density across the beam was measured calorimetrically with a 0.64-cm-diam probe that was scanned in front of the test sample. A resultant profile is shown in Fig. 5. Water flow through the swirl tubes was 0.19 L/s for all tests.

Typical hydrogen beam parameters included: energy = 26 keV, total extracted current = 6 A, pulse length = 1 s, and frequency = 0.1 s^{-1}. The full width of the beam was ~13 cm with a peak power density of ~4.3 kW/cm^2, as shown in Fig. 5. Integration under the curve yielded an average power density of ~1.7 kW/cm^2. The species ratio, $f_{H_1^+}:f_{H_2^+}:f_{H_3^+}$, of the extracted ions was assumed to be approximately 0.6:0.2:0.2 (Ref. 6). It was also assumed that the H_2^+ and H_3^+ ions were fully dissociated, so that the average particle flux rate was

$$\frac{\text{average power density}}{\text{beam energy}} \times \frac{f_{H_1} + 2f_{H_2} + 3f_{H_3}}{\text{electronic charge}}$$

$$= \frac{1.7\ \text{kW/cm}^2}{26\ \text{keV}} \times \frac{0.6 + 2(0.2) + 3(0.2)}{1.6(10^{-19})\ \text{C}}$$

$$= 6.5 \times 10^{17}\ \text{particles/cm}^2\cdot\text{s} .$$

Helium beam parameters were: energy = 25 keV, total extracted current = 5.1 A, pulse length = 1 s, and frequency = 0.1 s^{-1}. The full width of the beam was also ~13 cm, with a peak power density of ~4 kW/cm^2 for an average power density of ~1.4 kW/cm^2. The resulting average particle flux density was ~3.5 × 10^{17} particles/cm^2·s.

EXPERIMENTAL RESULTS

The material test samples were exposed to the described particle beams to first test their survivability to a few 1-s-long pulses. If the samples survived (no melting, spalling, or peeling) exposure was continued for 4000 s (hydrogen beam) or 2000 s (helium beam). The resulting mass loss was

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[a]Plasma spraying is a method of coating objects by feeding a powder of the material to be deposited into a plasma arc, where the powder is melted and propelled to the object.

[b]A fine-grain, high-strength graphite produced by Union 76 Oil Company.

[c]Ticusil, a silver/copper brazing alloy containing ~4.5% titanium, is a product of WESGO Division, GTE Products Corporation.

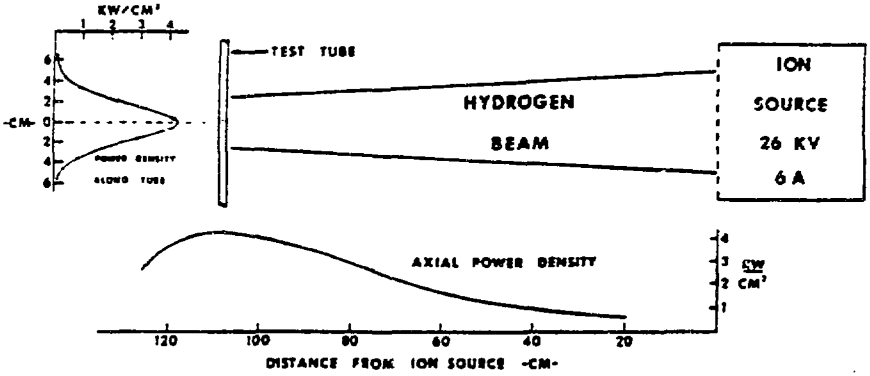

Fig. 4. Test arrangement.

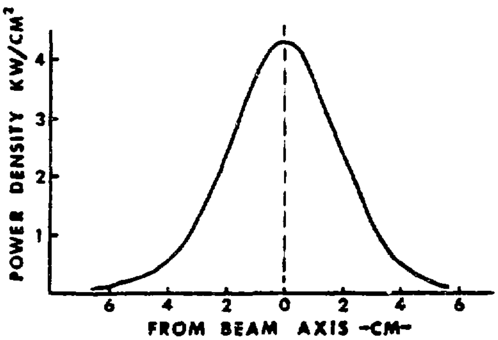

Fig. 5. Beam power density profile.

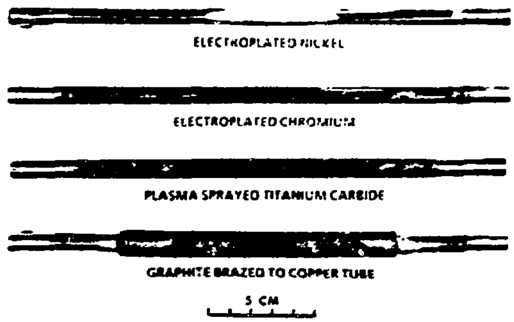

Fig. 6. Examples of test samples after extended exposure to beam.

determined by weighing each sample before and after each run.

A. Survivability

Survival results were fairly encouraging. The samples of plasma-sprayed TiC and Cr; the electroplated Cr, Ni, Ag, and Au; the graphite with slits 1.3 cm apart; the graphite having 2.5-cm segments; and the uncoated copper tube all survived peak power densities of ~ 4 kW/cm^2. Figure 6 shows examples of tubes after 4000- or 2000-s total exposure to particle beams.

The plasma-sprayed nickel and aluminum samples did not survive 4 kW/cm^2. These coatings did not seem to adhere well to the copper and melted in the area of peak power when thermal contact was lost. See Fig. 7. The power level at which the plasma-sprayed nickel coating would survive was not determined. The plasma-sprayed aluminum coating was found to survive a peak power density of ~ 2 kW/cm^2. An aluminum sample was then exposed for 4000 s with the hydrogen beam at a peak power level of ~ 1 kW/cm^2. The mass loss could not be determined.

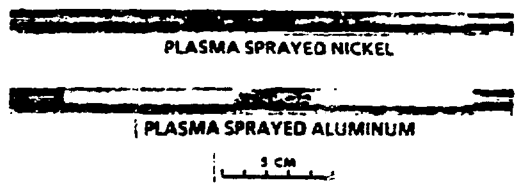

Fig. 7. Test sample failures.

The sample with a single 12.7-cm-long graphite shell withstood ~ 3 kW/cm^2 peak power density, but at ~ 3.5 kW/cm^2, graphite spalled away from a fairly large area. See Fig. 8. Thermal stress became too high to be relieved by the single piece.

The previously discussed TiC samples were tested in an "as sprayed" condition. Two additional TiC samples were sprayed more thickly and then centerless ground to the 0.13-mm thickness to produce a surface smoother than "as sprayed." When tested, the samples displayed "hot spots" where the coating blistered and became overheated. The

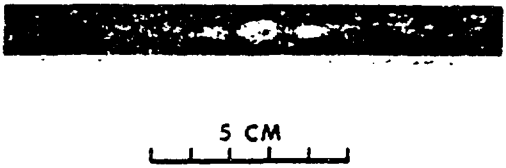

Fig. 8. Spalled graphite sample.

coating on one of these samples peeled away from the tube in a long strip. The grinding operation may have weakened the adhesion of the TiC to the copper.

B. Erosion

There are several processes that could be involved in causing the erosion and resultant mass loss by energetic particles in this experiment. These processes include physical sputtering (including chemically enhanced), chemical sputtering, evaporation, and sublimation. These processes have varying dependences on particle energy, angle of incidence, surface temperature, and surface smoothness. We believe the primary process involved in this experiment was physical sputtering.

We therefore attempted to make a comparison between our data and reference sputtering yields.[7] An effective sputtering yield N_{SP}/N_B [atoms/particle (ion)] was determined for our data, where

$$N_{SP} = \frac{\text{mass loss (g)}}{\text{1 mole (g)}} \times 6.023 \times 10^{23}\ \text{(particles/mole)}$$

and

$$N_B = \text{average particle flux} \left(\frac{\text{particles}}{\text{cm}^2\cdot\text{s}}\right)$$

$$\times\ \text{area (cm}^2\text{)} \times \text{time (s)}\ ,$$

where

$$\text{area} = \text{beam full width (cm)} \times \text{sample diameter (cm)}\ .$$

For hydrogen (H_2) beam cases, a resultant reference sputtering yield S_R (atoms/ion) was determined for the composite (H_1^+, H_2^+, H_3^+) beam using reference sputtering yield (S) values and species ratio (f_{H_1}:f_{H_2}:f_{H_3}):

$$S_R = \frac{f_{H_1} S(E) + 2f_{H_2} S(E/2) + 3f_{H_3}(E/3)}{f_{H_1} + 2f_{H_2} + 3f_{H_3}}$$

where $S(E)$, $S(E/2)$, and $S(E/3)$ are reference sputtering yields at full energy, one-half energy and one-third energy, respectively.

Results for all samples tested are tabulated in Table 1. From the standpoint of both mass loss and sputtering yield, TiC is the most erosion-resistant material tested. Graphite tested well too, with low mass loss. Of the metals, chromium and nickel have fairly low sputtering yields. It can be seen that the sputtering yields determined from this study are greater than the reference values by about a factor of 2 or greater. Several factors could explain these differences: namely, the processes other than sputtering that may have taken place and the differences in conditions during this study from those during which the reference data were taken. For example, the cylindrically shaped samples used in this study presented a surface that caused the incident angle of bombardment to vary between 0° and 90°. Also, the temperatures of the sample surfaces varied with the power density profiles of the beams.

Two test samples (TiC and electroplated Cr) were examined with a scanning electron microscope (SEM). Three areas (unexposed back surface, exposed front surface, and exposed side surface) of each are shown in Figs. 9 and 10. The titanium carbide, being plasma-sprayed, is quite rough. The exposed front surface has the appearance of a uniformly etched surface, while the side area has primarily the high spots removed by the obliquely incident particles. The chromium surface has nodules and striations or microcracks. Particle erosion appears to be greater along the striations.

CONCLUSIONS

The results to date are encouraging and, along with further study, should provide information important in the development of functional rf launchers, Faraday shields, limiters, and divertor collector plates.

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Table 1. Results for all samples

	Material							
	Graphite	TiC	Cr	Cr	Ni	Cu	Ag	Au
Coating type[a]		PS	EP	PS	EP		EP	EP
Hydrogen beam								
Mass loss, mg	18	17	38		62	132	256	228
N_{SP}, $\times 10^{20}$ atoms	9.0	1.7	4.4		6.4	12.5	14.3	7.0
N_B, $\times 10^{22}$ particles	2.1	1.6	1.6		1.6	1.6	1.6	1.6
N_{SP}/N_B, atoms/particle	0.04	0.01	0.03		0.04	0.08	0.09	0.04
S_R, atoms/ion		0.006			0.006	0.01	0.03	0.01
Helium beam								
Mass loss, mg	23	25	124	94	201			
N_{SP}, $\times 10^{20}$ atoms	12	2.5	14	11	21			
N_B, $\times 10^{22}$ particles	1.2	0.84	0.84	0.84	0.84			
N_{SP}/N_B, atoms/particle	0.10	0.03	0.17	0.13	0.25			
S_R, atoms/ion								

[a]PS = plasma sprayed; EP = electroplated.

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Fig. 9. TiC micrographs, 1000×.

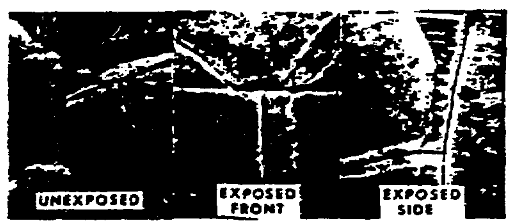

Fig. 10. Cr micrographs, 1000×.