MASTER

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To: Dr. C. Finfgeld
Materials and Radiation Effects Branch
Office of Fusion Energy
Department of Energy
Washington, D.C. 20454

Subject: Annual Report:

Deuterium Plasma-Material Wall Interactions

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ABSTRACT

During the past year we studied in detail plasma-first wall material damage induced by unipolar arcing. Unipolar arcing damage was analyzed as a function of material, surface preparation and microstructure. Unipolar arcing was found on all materials tested and the percentage of the surface area affected by arcing was similar for different metals. The severity of unipolar arcing was found to be very sensitive to microstructure. This was deduced through extensive study of different heat treatments of Ti-6Al,4V.

I. ACTIVITY

During the past year we have continued our research into the physical effects caused by the interaction of a hot, dense deuterium plasma and materials. We finished analysis of our data taken during the previous year and analyzed unipolar arcing damage as a function of material irradiated, surface preparation and microstructure. The majority of our findings were reported on in great detail in a doctoral thesis.¹

As outlined in last year's progress report we have concentrated on the damage mechanism unipolar arcing because of its potential as a very potent source of impurities that could find their way into the plasma. The need for the recent DOE workshop on arcing in fusion devices perhaps substantiates our concern.² By irradiating materials in our plasma shock tube we have sought to understand the effect of metallurgical variables on the severity of damage by unipolar arcing.

We initially believed that the refractory metal alloys would exhibit less arcing damage than the stainless steels because of their ability to emit electrons thermionically and to form incandescent cathode spots instead of erosive ones.³ But our experience with refractory metal alloys and with stainless steels containing refractory metals would seem to indicate otherwise.

Figure #1 shows the percent area coverage by unipolar arcing for a number of different alloys as a function of number of plasma pulses of the shock tube. As can be seen, the refractory metal alloys exhibit approximately half the coverage shown by the stainless steels. But this coverage

of 4% (at 1000 pulses) is still severe. The reason that our refractory metal alloys exhibit arcing may be due to the short duty cycle of the shock tube (1 μ sec) which limits the amount of heating by the pulses.

It can also be seen that the coverage of 316 stainless steel differs only slightly from that of 304 stainless steel despite the presence of the low work function element molybdenum in the 316 SS. Also the presence of the low work function element, zirconium, in Nb-751 does not change the amount of arcing damage it suffers in relation to pure niobium. Thus the fact that a material contains a lower work function alloying addition does not necessarily decrease the severity of arcing.

In order to verify whether thermionic current emission would prevent arcing on materials we have built and tested a device to heat samples in situ in the shock tube. This device will heat specimens to the expected first wall operating temperature of 550°C where the thermionic electron current should be greater. This device will also be used to determine how arcing will be effected by temperature induced changes in microstructure, such as precipitate coarsening and dislocation recovery.

We have made estimates of the erosion resulting from unipolar arcing. Using published figures for mass loss due to arcing and on current density of arcs⁴ we can make estimates of the amount of material carried into the plasma during an anticipated tokamak discharge. Using the first wall area and volume anticipated for a power reactor and our value for area coverage by arcs it can be shown that an impurity concentration of about 10^{14} atoms/cm³ could potentially result during one tokamak discharge.^{1,5} This is greatly in excess of the concentration of ferrous impurities (about 10^{11} /

cm³)⁶ necessary to prevent ignition in anticipated fusion power reactors.

During the past year we have also extensively studied the effects of our plasma upon Ti-6Al,4V. Our reason for doing this has been twofold. First of all Ti-6Al,4V has been recently proposed as an alloy for use in potential fusion power reactors and present day plasma devices.⁷ Secondly, Ti-6Al,4V is a two phase alloy capable of having it's microstructure altered by appropriate heat treatments. This enabled us to further test out some of our ideas on the occurrence of unipolar arcing.

For our study we selected three widely different microstructures of Ti-6Al,4V to irradiate. They included:

- i) mill annealed condition, a normalized structure with approximately 5% β content
- ii) recrystallized condition, approximately 12% β located in a semicontinuous intergranular phase
- iii) solution treated and aged condition, an aged martensitic structure.

These microstructures are shown in Figure #2. We observed the same characteristic damage as previously observed in other material systems.^{5,8,9}

It was observed that surface damage on the Ti-6Al,4V specimens exceeded that seen on stainless steels and refractory metal alloys. Our initial emphasis on unipolar arcing was redirected to include the damage effects due to blistering and cracking. It was observed that blisters formed on Ti-6Al,4V sooner than on any other material and also that surface cracking was more severe. (see Figure #3)

Unipolar arcing is a damage mechanism that will contribute to the poisoning of the plasma. Blistering and the surface cracking observed are effects of the deuterium implanted in the material as well as due to the thermal fatigue inherent in our device. In conjunction with Grumman Aerospace Corporation we used a nuclear microprobe to determine deuterium profiles of the three different heat treatments. At this stage results are still being discussed between Grumman and Columbia.

To see if the observed surface cracking was intra-granular or inter-granular (indicative of an embrittling mechanism) we used KEVAX, an energy dispersive X-ray analysis system. It was necessary to use this method because the initial etched microstructure was no longer evident after irradiation in most cases. Compositional differences, namely the segregation of vanadium to the β phase, allowed us to show that the cracking was indeed intergranular between the α and the β phases. (Figure #4) Accordingly hydrogen (deuterium) embrittlement has taken place in this alloy.

The unipolar arcing damage of all three different treatments of Ti-6Al,4V was extreme. Figure #5 shows the coverage by unipolar arcs for two of the heat treatments and also for the stainless steels and the refractory metals we tested. The large blisters on the recrystallized condition specimens of Ti-6Al,4V prevented an accurate determination of arcing coverage. But incomplete data suggests that the coverage would trail behind the other two heat treatments.

This data is consistent with our earlier developed model of arcing coverage as a function of surface interface density. The solution treated (martensitic) condition has the highest density of interfaces and hence

the highest density of arc initiation sites. It showed the greatest coverage by unipolar arcing damage. The mill annealed condition which has a less dense interface network showed less coverage. The recrystallized condition with the least density of interfaces showed the least coverage by arcing. Thus the greater the amount of interfaces the greater the number of arc initiation sites and the arcs tend to grow large. This difference in unipolar arcing coverage among the three different heat treatments was overshadowed by the unexpectedly drastic difference in unipolar arcing coverage between the titanium samples the stainless steels and the refractory metal alloys.

As mentioned, significant ejection of wall material into the plasma can prevent fusion ignition by the loss of energy through line radiation. This mechanism becomes more severe as the atomic number, Z , of the impurity atom goes up. With this in mind, low Z materials such as graphite are being considered for use as limiters and first wall coatings. However, even in the case of low Z graphite, there is still the question of how much material will be ejected into the plasma.

In order to directly measure the erosion rate of graphite in our shock tube we have built a relatively simple residual gas analyzer system utilizing a monopole mass spectrometer. This system will enable us to investigate the species of impurities given off into our plasma and their relative amount.

During earlier runs on the shock tube with graphite in place the gas pressure of the system was significantly higher after a repetition of the shock tube than before the pulse was fired. This effect persisted even

after 100 pulses of the shock tube when the initial and final pressures should have been the same. This pressure rise did not take place when metallic samples were in place in the shock tube for more than 100 pulses. The value of the rise in pressure can be used to compute an effective sputtering rate of 10^3 atoms per incident ion. This high rate is suggestive of unipolar arcing. Figure #6 shows typical micrographs of graphite damage after 100 and 1000 plasma pulses.

During the coming year we will complete work in three areas that we began during this past year:

- i) irradiation of Ti-6Al₄V
- ii) identification of amount and species of material ejected from ATJ graphite during irradiation
- iii) the effect of higher bulk temperature on damage modes.

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II. PUBLISHED PAPERS, LECTURES, etc.

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R.N. Jarrett, J.K. Tien, N.F. Panayotou, R.D. Stevenson, J.C. Desko and R.A. Gross, "Interaction of A Hot, Dense Deuterium Plasma With Ti-6Al, 4V," presented at 108th Annual AIME meeting, New Orleans, LA, 18-22 Feb. 1979.

R.D. Stevenson, J.K. Tien, and R.A. Gross, "Unipolar Arc Damage of Materials In A 600 eV Deuterium Plasma," presented at and published in Proceedings of DOE Workshop, "Arcing Phenomena in Fusion Devices," held at Knoxville, TN, 5-6 April, 1979.

III. BUDGET AND PERSONNEL

For this past year our expended funds were within our budget.

Personnel employed by this contract during the past year were:

Faculty: Prof. John K. Tien

Prof. Robert A. Gross

Graduate Students: Nicholas F. Panayotou

Roland D. Stevenson

John C. Desko

Robert N. Jarrett

Staff (all part-time): Moe Cea

John Osarczuk

Joe Diamond

Jake Harris

Dana Gudan

Cathy Gallegos

The High Resolution Scanning Diffraction Device (\$10,200) ordered during the first year of our contract period was received during this past year completing our capital equipment purchases for our two year contract period.

Respectfully submitted by:

John K. Tien

Robert A. Gross

Handwritten signatures of John K. Tien and Robert A. Gross. The signature of John K. Tien is written over the printed name "John K. Tien" and the signature of Robert A. Gross is written over the printed name "Robert A. Gross".

Figure #1. Percent area coverage due to cathode spot remnants as a function of plasma exposure for the stainless steels and the refractory metals and alloys. Note that the coverage even for these distinct metal systems is within a factor of 2.

Recrystallized

Vacuum Annealed

Solution
Treated and Aged

Ti-6Al-4V MICROSTRUCTURES

Figure 2

SURFACE CONDITIONS AFTER EXPOSURE TO PLASMA

Vacuum Annealed

Recrystallized

Solution Treated and Aged

Figure 3

GRAIN BOUNDARY CRACKING IN RECRYSTALLIZED Ti-6Al-4V

ALPHA PHASE

BULK

BETA PHASE

Figure 4: EDAX verification of grain boundary cracking

FIGURE #5

a.

b.

Figure 6: Scanning micrographs of graphite after 100 plasma pulses (a), and after 1000 plasma pulses (b).