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Experimental measurements of surface damage and residual stresses in micro-engineered plasma facing materials

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HIGHLIGHTS

- Refractory metals with micro-engineered surfaces are developed as heat shields for high heat flux applications.
- Tungsten with micro-pillar type surface architecture is shown to have significantly reduced residual stresses after plasma exposure.
- X-ray diffraction (XRD) spectra of the W-(110) peak reveal that broadening of the FWHM for micro-engineered samples is small.
- Spectral shifts of XRD signals show that cyclic plasma heat loading anneals out built-up residual stresses in micro-engineered surfaces.

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ABSTRACT

The thermomechanical damage and residual stresses in plasma-facing materials operating at high heat flux are experimentally investigated. Materials with micro-surfaces are found to be more resilient, when exposed to cyclic high heat flux generated by an arc-jet plasma. An experimental facility, dedicated to High Energy Flux Testing (HEFTY), is developed for testing cyclic heat flux in excess of 10 MW/m^2. We show that plastic deformation and subsequent fracture of the surface can be controlled by sample cooling. We demonstrate that W surfaces with micro-pillar type surface architecture have significantly reduced residual thermal stresses after plasma exposure, as compared to those with flat surfaces. X-ray diffraction (XRD) spectra of the W-(110) peak reveal that broadening of the Full Width at Half Maximum (FWHM) for micro-engineered samples is substantially smaller than corresponding flat surfaces. Spectral shifts of XRD signals indicate that residual stresses due to plasma exposure of micro-engineered surfaces build up in the first few cycles of exposure. Subsequent cyclic plasma heat loading is shown to anneal out most of the built-up residual stresses in micro-engineered surfaces. These findings are consistent with relaxation of residual thermal stresses in surfaces with micro-engineered features. The initial residual stress state of highly polished flat W samples is compressive ($\approx$ -1.3 GPa). After exposure to 50 plasma cycles, the surface stress relaxes to -1.0 GPa. Micro-engineered samples exposed to the same thermal cycling show that the initial residual stress state is compressive at (- 250 MPa), and remains largely unchanged after plasma exposure.

1. Introduction

Plasma-facing materials (PFM) are required for a great number of technological applications, encompassing space electric propulsion devices, micro-electronics fabrication, fusion energy conversion, and pulsed power devices, just to name a few. Continued development of space Electric Propulsion (EP), fusion energy, and Pulsed Power (PP) systems relies on fundamental advances in our understanding of material performance and survival in extraordinarily severe environments. The demand of higher performance materials is even greater in future technologies that will require materials to operate in substantially more aggressive environments. In such applications, PFM encounter unprecedented severe thermomechanical environments, as plasma ions and electrons slam onto the surface. Many physical degradation phenomena ensue, including material loss by ablation, blistering, sputtering and evaporation, as well as genuine thermoemchanical damage in the form of extensive plastic deformation and complex surface

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cracking. The environment severity is correlated with two main parameters. The first is the total amount of absorbed energy density that passes through the surface, Γt (kWh/cm^2); a measure of the material lifetime. The second load-related parameter is the instantaneous heat flux, Γ (MW/m^2). While Γt is indicative of the duration through which the material will have to survive successive amounts of energy, delivered to its surface either continuously or intermittently, Γ is associated with the response time scale of the material itself to instantaneous pulses of energy. Generally, if Γ is high, the material lifetime is low, and vice-versa.

If the incident heat flux is below $\approx$ 0.1 MW/m^2, active cooling may not be required and many of today's EP devices (e.g. Hall thrusters) are passively cooled. However, for more demanding applications and future devices, active cooling is required and significantly higher heat fluxes are expected. In Hall thrusters, the ion power is 0.05 MW/m^2, and the electron power is 0.8 MW/m^2, resulting in rapid erosion of the insulating boron nitride rings, and thermo-mechanically induced fractures. The current limits of the energy fluence are on the order of 3 TJ/m^2 and 50 TJ/m^2 for ions and electrons, respectively. In ion thrusters, the cathode is a highly stressed component, receiving ion powers of 0.05 MW/m^2, and reaching an energy fluence of 7.5 TJ/m^2 at the end of life. On the other hand, the screen grids in ion thrusters receive only 0.0025 MW/m^2 of ion flux, and because of their critical design location, survive only to an energy fluence of 0.4 TJ/m^2. The aggressive environments of Magneto Plasma Dynamics (MPD) thrusters requires instantaneous electron power of 8 MW/m^2 and ion power of 1.6 MW/m^2, and because of the pulsed operation, the lifetime energy fluence is 0.5 TJ/m^2 for electrons and 1.0 TJ/m^2 for Li ions.

Fig. 1 shows the dependence of the lifetime FOM (Γt, kWh/cm^2) on the instantaneous heat flux (Γ, MW/m^2), carried by plasma ions, photons, and electrons, in a number of space electric propulsion and energy applications. The figure shows approximate FOM limits for current state-of-the art technologies (light green region). This includes some common technologies, like turbine blades of jet engines, photo-voltaic solar cells, as well as comparable technologies under development (e.g. fusion energy). The FOM is in the range 100–600 kW h/cm^2 for the most demanding present day technologies. To achieve greater lifetimes in the future (e.g. in excess of 1000 kWh/cm^2), new materials with special surfaces must be developed.

Severe plasma transients are expected to greatly influence the integrity of plasma-facing components in fusion energy systems, notably the tungsten armor in most of existing divertor designs. Typical design-base transients contain an amount of energy in between 0.1 and 0.5 MJ/m^2 for the Joint European Torus (JET) and between 1 and 5 MJ/m^2 for the International Tokamak Experimental Reactor (ITER), lasting a duration between 0.1 and 1 ms, respectively. Such transients are expected to cause surface fracture, plasticity, and grain motion in polycrystalline tungsten. Among the operational scenarios of interest is the response of tungsten to edge localized modes, which carry energy densities on the order of 1 MJ/m^2 and time durations in the range of 0.1–0.5 ms, which can result in severe damage to the tungsten armor in the form of cracking and localized melting of the material [1]. Cyclic thermal transients are generally associated with complex plasticity and fracture phenomena. In particular, the response of a material facing cyclic high heat flux loading can be either elastic, plastic, ratcheting, shakedown, or fracture. Ratcheting is the continuous accumulation of plastic strain with each passing cycle up to the point of failure, and is considered detrimental. Shakedown describes an initial degree of plastic deformation, quickly reaching equilibrium in subsequent loading cycles. A detailed analysis of the residual stress state of the micro features comprising the coating is necessary to provide an avenue for improvement in the coating process. If the surface layer is structured so as to allow expansion and contraction without these large residual stresses, one might be able to develop a material that is more resistant to high heat flux thermomechanical effects. We have recently developed such a material concept, where an “armor” coating is deposited by CVD on top of the main structure, with the main function being thermomechanical damage mitigation [2]. The present work extends the experimental investigations presented in Ref. [2].

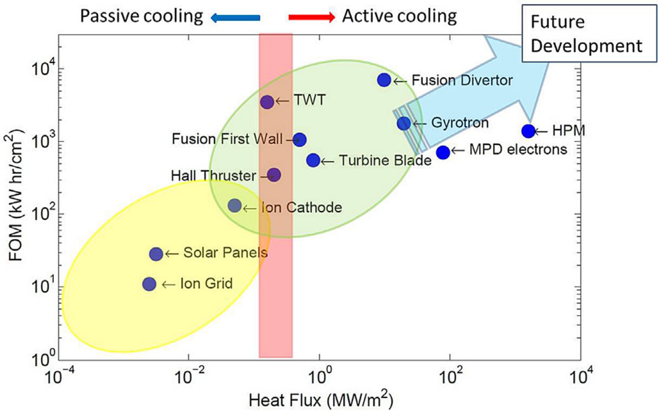

Fig. 1. Lifetime Figure-Of-Merit (FOM) metric of plasma-facing materials measured in kWhr/cm^2, as a function of the incident heat flux (rough indicator of environmental severity).

A number of researchers have attempted designing refractory metal coatings from a traditional standpoint where a flat surface is deposited onto a substrate and exposed to a thermally harsh environment [3–6]. Although efforts along this path have proved successful in protecting the underling structure, improvements are still achievable through the advent of castellated armor concepts [2]. In such designs, free-standing structures, such as micro-pillars are grown onto a surface, and are capable of protecting it through reduction of residual thermal stresses. Similar concepts have been proposed at a macroscopic scale, yet function largely in the same way [7,8]. A unique multiphase material system is developed and investigated here. Experimental results characterizing the mechanical response of surfaces designed with coatings of uniform micro-pillar geometry, each comprised of a rhenium core surrounded by a tungsten shell, will be discussed here. The composite nature of microarchitected surfaces, coupled with the mechanical strength and ductility furnished by small feature size, make these material concepts suitable for shielding the underlying structure from the effects of severe plasma transients. The experimental effort presented in this article will aim to show that the plastic distortion induced by thermal loading of microarchitected surfaces is mitigated relative their planar counterpart. The reduction of plastic distortion in microarchitected surfaces brings to light the tailorable properties of such coatings, providing designers with a material capable of withstanding a range of extreme environments and not limited to the intrinsic materials properties of a monolithic planar surface. The introduction of new surface design variables, such as geometry of constituent features, in addition to material selection offers an opportunity in thermal shielding technology.

The objective of this work is to develop plasma-resilient, micro-engineered, refractory metal armor (coating) to resist thermal shock and harmful thermal residual stresses during severe plasma transients. The focus is on manifestations of thermomechanical damage in the form of surface fracture and residual plastic stresses,