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Development of micro-engineered textured tungsten surfaces for high heat flux applications

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ABSTRACT

Surface micro-engineering can enhance the thermo-mechanical performance of plasma facing components (PFCs). For example, castellation of a surface can reduce thermal stress due to high heat loads and thus provide higher thermo-mechanical resilience. Recently, fabrication of a variety of micro-sized refractory dendrites with reproducible geometric characteristics (e.g., density, length, height, and aspect ratio) has been demonstrated. In contrast to flat surfaces exposed to high heat loads, dendrites deform independently to minimize near-surface thermal stress, which results in improved thermo-mechanical performance. Thus, the use of dendrites offers a unique micro-engineering approach to enhance the performance of PFC structures. A brief overview of W, Re, and Mo dendritic structures is given along with micrographs that show dendrite-coated surfaces. The thermal responses of representative dendrite structures are analyzed as a function of aspect ratios and dendrite geometry. The heat-management capability of needle-like dendrites exposed to a surface energy of up to 1 MJ/m^2 is analyzed and compared to a flat surface. It is concluded that dendrite structures can significantly reduce thermal stress in the substrate when compared to flat surfaces. Implications of dendritic surfaces on sputter erosion rates are also discussed briefly.

1. Introduction

Due to a larger volume of material, micro-engineered surfaces can accommodate higher surface loads than flat armor. This knowledge can be used to improve the thermo-mechanical response of plasma-facing component (PFC) surfaces to high heat and charged particle loading. Micro-engineered structures would have geometric features with characteristic length scales on the order of microns or sub-microns. Common examples of micro-engineered structures include etched surfaces [1]; castellated structures, tungsten brush limiters [2]; plasma-sprayed coatings; open cell foams, and velvet or fiber carpet coated surfaces [3].

A new category of micro-engineered surfaces has been developed in recent years: dendrite-needles and dendrite-nodules. These are highly textured coatings, which effectively create micro-castellated surfaces. Relative to a flat surface, such dendrites allow for more freedom of expansion and contraction. Thus, dendritic surface coatings are able to undergo some level of distortion, independent of the substrate, thereby minimizing the thermal stress encountered in conventional (smooth and fully dense) tungsten structures when exposed to high heat loads.

The technology to fabricate dendrite structures with reproducible features is relatively new. Therefore, in this introductory paper we first discuss the rationale of using textured surfaces (Section 2). Next, in Section 3 we introduce the current dendrite fabrication technology and present micrographs of W, Re, and Mo dendrite coatings. In Section 4, we present experimental measurements and transient thermal analyses results of dendritic coatings exposed to energetic pulsed ions [4,5], which substantiate the enhanced heat-load handling capabilities of dendritic coatings. Finally, through analysis, in Section 5 we show a significant reduction in thermal stress of tungsten dendrite structures to pulsed high surface-heat loads compared to that of flat tungsten structures. The paper concludes with a few statements regarding preliminary sputtering analysis results of dendritic coatings.

2. Rationale for micro-engineered coatings

Tungsten exposed to high surface-heat loads develop surface cracks in both slow transients (few sec) and edge-localized mode (ELM)-like (<1 ms) loadings of ∼1 MJ/m^2 and disruptions of several 10 MJ/m^2 [4]. During cool down, large stresses are induced in the heated surface layer following plastic deformation due to thermal expansion. Depending on tungsten material, power loading, and substrate base temperature, in addition to minor cracks of a few tens of μm deep, a network of major cracks can develop with depth

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of several hundred μm and width of 2–10 μm [6–8]. Thus, for ITER-like ELMs ranging between 0.1 and 1 MJ/m^2 and lasting between about 0.1 and 1 ms the formation of cracks seems unavoidable. Micro-engineering surfaces consisting of dendrites could reduce the formation of networks of cracks. The three major potential benefits of dendritic refractory surfaces PFCs:

(1) Higher heat load capability, due to increased surface area and quasi-volumetric heat deposition instead of purely surface loading.
(2) Reduced potential for crack initiation, due to the presence of the dendrites, which absorb most of the heat and then conduct it to the substrate. In effect, the dendritic surface is the ultimate in "castellated" (tiled) surfaces, which reduce thermal stresses and thus cracking.
(3) Reduced subsurface implantation depth of high-energy helium. A high aspect ratio (height/diameter) dendrite has very shallow ion impingement angles along the sides, which results in a significant reduction in the depth of penetration of ions compared with flat surfaces.

The load-handling capacity of dendrite-coated surfaces increases by distributing the load on three-dimensional structures, resulting in pseudo-volumetric loading. Because the micron-sized W-dendrites are capable of a greater level of distortion than conventional smooth flat W-surfaces, thermal stress is reduced and greater ductility is exhibited. The dendritic coating provides a large increase in surface area, which promotes better heat distribution and minimizes net erosion losses. Furthermore, the release of refractory dust from the surface is reduced due to trapping within the textured surface structures.

For IFE (Inertial Fusion Energy), a significant concern is the impact of high-energy helium implantation on surface helium bubble growth in PFCs. The implantation angle of normal incident particles is reduced from near normal ~90° to about 6° for a dendrite needles with an aspect ratio of 10 and the effective penetration depth of high energy helium ions can thus be reduced significantly, i.e., by a factor of 5 for 1.6 MeV He. Therefore, helium residence time in the material can be reduced in the dendritic structure, which facilitate near surface implantation, shorter release path lengths thus minimizing formation of bubbles and blisters. Potential of increased sputtering losses due to the low impingement angles are the subject of ongoing experimental work to be reported at a later time. However, initial modeling efforts have shown that net sputtering might be greatly reduced due to re-deposition on near-by dendrite structures [10].

From a material stability point, it is important to note that the dendrites are produced using chemical vapor deposition (CVD). Control of impurity levels and grain morphology in CVD-produced refractory metals exceeds that of PM materials, resulting in improved thermal and mechanical performance of CVD materials (e.g., reduced impurity driven embrittlement). Thus, fragmentation and dust formation due to high-energy pulsed heat loads, commonly observed in refractory metals fabricated by plasma spraying or conventional powder metallurgy is expected to be much lower in dendritic coatings.

3. Development of textured refractory coatings

Many demanding applications where high surface-heat flux are imposed on component surfaces, in rocket engines, aerospace vehicle thermal protection systems, and a variety of military and civilian X-ray and laser applications employ high-purity (~99.99% pure) tungsten and other refractory metals fabricated by CVD. CVD-based refractory metals do not suffer the embrittling effects associated with light element impurities or inherent residual stress common with tungsten parts produced via powder processing techniques. In the CVD process, materials are built at the atomic level, allowing for control of grain size, shape, and orientation to optimize thermal and mechanical behavior. The CVD process is a versatile and relatively inexpensive method of molecular forming of materials and structures that are difficult to create by conventional powder processing and machining.

3.1. Rhenium dendrites

Ultramet Inc. [11] has developed technology that varies CVD process conditions of temperature, pressure, reactant material flow rates and concentrations to yield a variety of textured refractory coating materials and structures on refractory metals or on low activation steels. Examples of a Re dendrite coated substrates are shown in Fig. 1. A variety of Re-dendrite densities, aspect ratios, shapes, directions, and heights were produced by controlling the CVD process parameters. Fig. 1B shows extremely fine needle-like dendrites with micro-meter diameters and lengths reaching almost 100 μ. It is important to note that the specific geometric characteristics of these dendrites can be fabricated with very high reproducibility [11].

Ultramet applies these high-emittance dendritic Re coatings in a production environment to tungsten cathodes used in special-purpose, high-wattage discharge lamps for semiconductor microlithography. Mercury short arc lamps up to 8000 W are used primarily as a light source in the manufacture of microchips, liquid crystal displays, and printed circuit boards. These lamps are used in the semiconductor industry because of their strong radiation in the blue, violet, and ultraviolet spectral range. A high-magnification view of the ultrahigh surface area dendritic Re coated tungsten anode is shown in Fig. 1C. These components operate at 2973 K for 100,000 h. The emittance of "black" (dendritic) Re coating is 0.82 at 973 K and 1.00 at 2273 K. The dendrite size (length and diameter) can be altered as desired by varying the deposition conditions.

3.2. Tungsten-coated rhenium dendrites

The vastly different geometric features between Re and W-dendrite prompted the development of W-coated Re-dendrites. For certain applications, the use of needle-like W-dendrites might be preferred by coating Re-dendrites with a thin or thick layer of tungsten. Fig. 2A and B shows examples of Re-dendrites coated with a thin layer of W(Fig. 2A) and a thick layer of W (Fig. 2B). Of interest is the uniformity of the diameter and height of the W-coated Re-dendrites and the high-density, almost velvet-like, coverage of the substrate. The motivation for developing W-coated Re-dendrites is the promise of raising the temperature of the "black" Re-dendrite-coated lamps from 2973 K to even higher temperatures for increased efficiency.

3.3. Tungsten dendrites

CVD tungsten dendrites differ greatly from Re-dendrites in shape, geometry, and packing. The variation is under investigation, but is believed to be related to differences in crystal structures (Re:HCP, W:BCC). While Re dendrites are generally needle or spear like, tungsten dendrites appear nodular. Fig. 3A–D shows three different types of coarse CVD tungsten dendrites. Although all three types have the six-faceted surface structure, they differ in arrangement and in porosity. The cauliflower-like dendrites (Fig. 3A and B) are packed tightly together with little space between them and have relatively uniform size distributions. The star-like dendrites (Fig. 3C and D) show a much looser packing fraction with larger gaps between them and a relatively non-uniform distribution of