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# Plasma-erosion of Cu-nanoDiamond and W-nanoDiamond composites

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## Abstract

Copper alloys are being considered as heat-sink materials for first wall panels of the international thermonuclear experimental reactor due to their favorable thermal conductivity, mechanical strength and radiation resistance. These materials are required to withstand thermal, mechanical and neutron loads as well as operation under cyclic mode. Tungsten is currently under intense investigation for application as plasma facing material due to its high resistance to plasma erosion and moderate tritium retention. However, in both cases increased performance is desirable and alternative solutions are sought. Diamond has extremely high thermal conductivity and Cu-nDiamond and W-nDiamond nanocomposites produced by mechanical alloying are promising candidates for those purposes. Cu-nDiamond and W-nDiamond were produced by high and mild-energy ball milling and were subsequently consolidated by thermomechanical processes. Adequate cross-sections were exposed to cyclic high-energy plasma in the ISTTOK tokamak. Plasma erosion has been assessed by electron microscopy.

## 1. Introduction

One of the major obstacles to arrive at a commercial fusion reactor is the lack of suitable first wall materials that will allow competitive operating temperatures as well as minimization of part replacement during the reactor's lifetime. In consequence, development of appropriate wall materials plays currently a key role in fusion reactor technology.

Plasma facing materials around the fusion chamber must withstand high-energy charged particle fluxes, Bremsstrahlung and gamma-ray radiation together with high fluxes of ~14 MeV neutrons, which are expected to lead to considerable material damage. Refractory metals in general, and tungsten in particular, are currently under intense investigation for this application due to their high resistance to plasma erosion and moderate tritium retention [1]. However, increased thermal conductivity, thermal stability and room temperature ductility are still demanded from these materials for a commercial application.

Due to superior thermal conductivity, good corrosion resistance and adequate melting point, copper alloys have widespread use in thermal management applications and have been chosen for the International Thermonuclear Experimental Reactor (ITER) heat sinks at the first wall [2]. These materials are required to withstand relatively high thermal, mechanical and radiation loads, as well as to resist to chemically aggressive coolants. An increased performance is also desirable and alternative solutions are sought for long term improvement.

Generally, a microstructure refined to the nanometer scale improves the mechanical strength due to modification of plasticity mechanisms [3]. Moreover, high grain-boundary specific area raises the number of sites for annihilation of radiation induced defects [4]. However, the low thermal stability of fine-grained and nanostructured materials demands the presence of particles at the grain boundaries that can delay coarsening by a pinning effect. As a result, the concept of a composite is promising in the field of nanostructured materials.

The hardness of diamond renders nanodiamond dispersions excellent reinforcing and stabilization candidates [5] and in addition diamond has extremely high thermal conductivity. Consequently, Cu-nDiamond and W-nDiamond nanocomposites are promising candidates for thermally stable materials for nuclear fusion reactors. Two major challenges concern these material combinations: the low solubility and intrinsically difficult bonding of carbon phases with copper and, in contrast, the strong tungsten affinity for carbon which tend to form carbides. Both challenges can be tackled using mechanical alloying: high-energy milling can be used to achieve bonding and enhance strength and thermal stability in the case of copper, while milder milling can be effectively used to disperse nanodiamond phases in tungsten, preventing the equilibrium reaction and resulting in improved thermal conductivity. Hot extrusion and hot rolling can subsequently be used to produce consolidated nanocomposites.

## 2. Materials and methods

Nanodiamond particles with 4–5 nm [5] and pure elemental Cu and W powders were used as starting materials. Mechanical alloying was performed in a Retsch PM400 planetary ball. The nominal atomic compositions used were 7:3 for Cu-nDiamond and 6:4 for W-nDiamond. Stainless-steel balls with a diameter of 10 mm where used for Cu-nDiamond while WC balls with a diameter of 10 mm were used for W-nDiamond. The mill was operated, respectively, at 400 rpm for 10h and at 200 rpm for 4h. In order to prevent oxidation, the container was filled with Ar. The Cu-nDiamond milled powder was consolidated by hot extrusion using a conventional INSTRON tensile/compression machine after encapsulation in a pure copper can with 16 mm in diameter. The W-nDiamond milled powder was encapsulated in stainless steel and consolidated by hot-rolling at 1073 K.

The nanocomposites were inserted into the ISTTOK edge plasma (a-r=1-2 cm) and exposed to both cleaning discharges and plasma pulses. The plasma characteristics are: Te~Ti = 10-40 eV, n=0.5-2x$10^{18}$ $m^{-3}$ and $q_{//}$ = 0.1-1 MW/$m^2$. The power deposited on the Cu-nD and W-nD samples was, respectively, 15 W and 2.5 W with an effective exposure time of 1200 s.

The exposed materials have been observed by scanning electron microscopy with a FEG-SEM FEIXL30 and FEG-SEM JEOL7001 both equipped with an Energy Dispersive Spectrometer (EDS).

## 3. Results and discussion

Figure 1 shows the results obtained with the Cu-nDiamond material. Deep craters exist near the surface (Fig. 1 (b)) and EDS analyses showed that the craters are C-rich regions. Immediately below the crater region, the material exhibits an extremely fine microstructure (Fig. 1 (c)) similar to the non-exposed one. Nevertheless, careful inspection reveals some recrystallization.

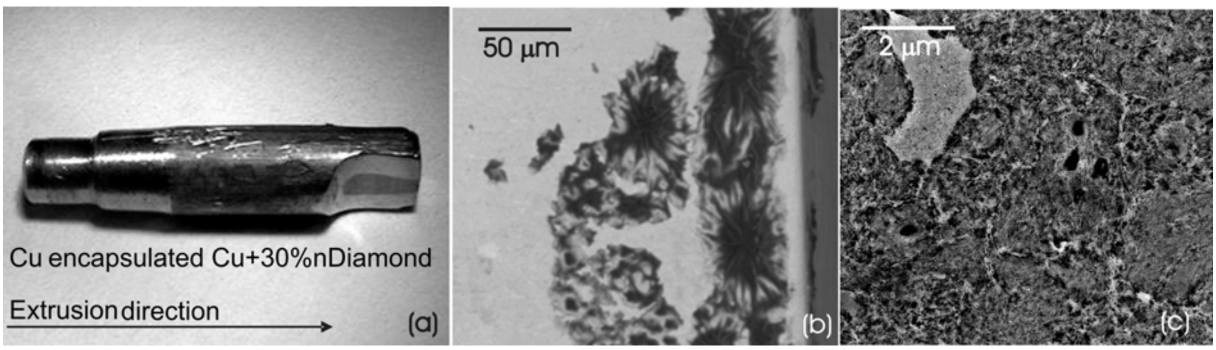


*Figure 1 – (a) Extruded Cu-nDiamond sample exposed to the edge plasma. (b) Cross-section perpendicular to B showing craters. (c) Cross-section parallel to B immediately below the crater zone showing an extremely fine microstructure.*

Figure 2 presents the results obtained with the W-nDiamond material. Zone 1 shows signs of intense evaporation (Fig. 2 (b)). Zone 2 shows carbide formation (Fig. 2(c)), whereas zone 3 presents eutectic dendrites formed by solidification (Fig. 2 (d)). EDS analyses showed that the internal region of the sample exhibited cracks filled with Fe and Cr, which originate from melting of the capsule (Fig. 2 (e)). On the left to zone 3 the material presents non-exposed characteristics (Fig. 2 (f)).

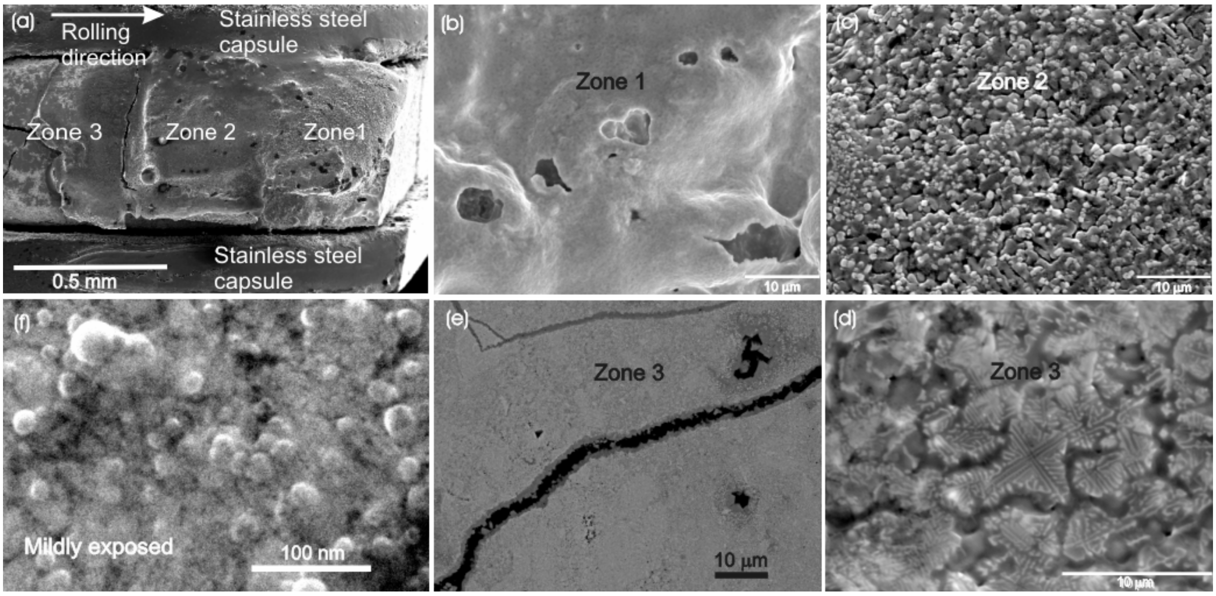


*Figure 2 – (a) Surface of the rolled W-nDiamond exposed to the edge plasma (perpendicular to B). (b) Surface displaying evaporation. (c) Surface with carbide formation. (d) Surface displaying eutectic dendrites. (e) Cross-section showing molten stainless steel inside cracks. (f) Mildly exposed material exhibiting a dispersion of nDiamond particles.*

In summary, the present results show that high-energy milling followed by thermo-mechanical consolidation can be used to prepare Cu-nDiamond and W-nDiamond nanocomposites. Optimization of consolidation parameters for W-nDiamond is currently being carried out at AIST. Long term and systematic plasma exposure experiments are planned at ISTTOK and at FTU (Frascati).

## 4. References

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