INTERNATIONAL ATOMIC ENERGY AGENCY

20th IAEA Fusion Energy Conference
1-6 November 2004 Vilamoura, Portugal

IAEA-CN-116

Recent Results in Plasma Facing Materials Studied at SWIP

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Abstract it is focuses on that multi-elements doped carbon base materials, tungsten coating and innovation liquid metal free surface for plasma facing materials (PFMs) researches at Southwestern Institute of Physics (SWIP), China. To reduce chemical sputtering and resist thermal shock of materials, it is developed using B_4C, Ti and Si doped graphite and C/C fiber composite (CFC), and their properties are investigated by experiments with special devices and HL-M Tokamak. For high Z PFM, Tungsten coatings on carbon and copper substrates are also developed. To understand the acting of substrate with different interface layers as the diffusion barrier of substrate, three different type tungsten coatings are compared studies on the investigation. They are the vacuum plasma spray tungsten coated (VPS-W) on CX2002U CFC with multi-layer tungsten and rhenium interface, inert gas plasma spray coating (IPS-W) on SMF700 graphite and IPS-W coatings coppers.

1. Introduction

In China, fusion materials research is included in national nuclear energy development project as a program of materials science (the National Natural Science Foundation Committee – NNSFC, the State Development and Reform Commission – SDRC, and the Ministry of Science and Technology – MOST support together the project). Of course, it will be coming for China fusion materials engineering researches with the world's fusion program have entered a new era after ITER built. So, up to now plasma-facing materials (PFMs) researches are focuses on the basic issues of the materials needed in current devices, next machines and future fusion reactor in this research program at Southwestern Institute of Physics (SWIP). In this paper, it are presented that thermal properties of multi-element doped carbon basic materials, properties comparing of several types tungsten coating on copper alloy and MHD stabilities experimental results of liquid metal free surface jet on a gradient magnetic field [1-4].

2. Multi-elements doped carbon basic materials

In spite of high tritium trapping and chemical sputtering yield, carbon-base materials will be still as a major plasma facing materials (PFM) in fusion device, such as, in most current tokamak machines and coming up ITER. To improve the material properties, the new types of multi-elements (Ti, Si, B_4C) doped carbon materials are developed in China. It is results of collaboration of Southwestern Institute of Physics, Institute of Coal Chemistry, Chinese

Academy of Science, The First Institute of Space Science & Technology Corporate and Institute of Plasma Physics Chinese Academy of Science. . The parameters of mechanical properties of the part of materials are shown in TABL 1.

TABE 1. THE PARAMETERS OF MECHANICAL PROPERTIES OF MULTI-ELEMENTS DOPED GRAPHITE MATERIALS

Materials No	Compositions (wt%) Ti	Si	B_4C	Density (g/cm^3)	Porosity (%)	Bend-resist Strength(MPa)	Thermal conductivity W/mK at 300K
GST126-01	5.5	12		1.954	11.3		105.54
GST315-01	2.5	15		2.110	8.67	97	278.25
GTB10610	6	10	10	2.18	4.18	67	
GB105		5	10	2.0	6.14	81.1	48.6
GBS3033		3	3	2.0	6.5	58.0	100.4
GBS33	3		3	1.94	8.1		100.0

The experimental results show that the synthesis effects are positive under Ti doped lower than 4t%, and the chemical sputtering yield are in the same level for the specimens, which the B_4C content are from 3%~ 10%, it is imply that only solid solution boron (Maximum solid solution of boron in carbon materials is about 2.8%) have a good effect on resistance chemical sputtering. But once Si doped up to 12%(to satisfy resistance RES), the positive synthesis effects are loss on chemical sputtering.

The results (mass loss rate) of thermal shock are shown in fig.1. It indicated that the mass loss rate decreases with B_4C doped increasing. These results can be understand in the term: major mass loss is due to the thermal emission of large particle of mass, and large particle of mass is produced by thermal stress fracture, so, for doped materials, during and after thermal shock, SiC and B_4C was melt in the first (melt points are 2100°C, 2450°C and 3500° C for SiC, B_4C and graphite, respectively), and the thermal stress was released, and lower.

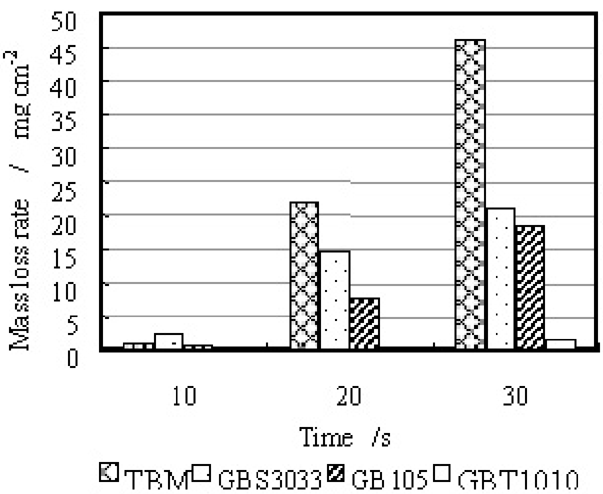
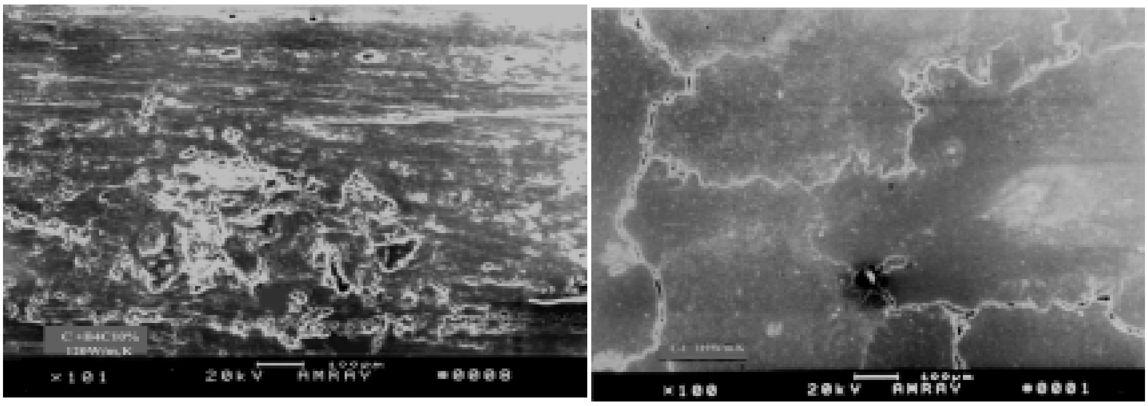


FIG.1. The mass loss rate of new type multi-doped graphite and purity graphite after Laser beam bombarded. (TBMS –purity graphite, The power density on surface of specimens is 122.9MWm^{-2} and 398.1 MWm^{-2}, and thermal shock strength is 0.78 KJ cm^{-2}.S$^{-1/2}$ and 2.52 KJ cm^{-2}.S$^{-1/2}$)

FIG.2 show the results of exposing specimen to plasma in HL-1M tokamak, where is 1cm closer to main plasma than that of limiter, exactly measured local plasma parameters is difficult, but for comparing the properties of two type different specimens, we need not exactly know the parameters. During exposure, specimens were turn over for the specimen surface keeping to electron side and to ions side in half a total time. After about 100 times charged, specimens were taken off to analyze. The results indicated that no significant cracking have been observed for doped carbon-base on materials, and on the other hand, the cracking was produced for purity graphite. For not cracking in doped carbon-base on materials specimens, one of the reasons is during and after plasma bombardment, SiC and B_4C firstly melt, and the thermal stress was released, and not cracking occurred.



(a). C/C+B_4C10% (b). Purity C/C composites

FIG. 2 SEM photograph of multi-elements doped(a) and non-doped carbon-base materials (b)after exposed to HL-1M tokamak (During plasma charged number from 6070$^{\#}$ to 6164$^{\#}$).

3. Tungsten coating characterize

As we know, tungsten maybe is the best plasma-facing material (PFM) if its ductibility can be improved to meet need. Before the properties of the material reaching the improvement, tungsten coating is another chose for using the high Z PFM in current fusion research devices. It is one reason of the tungsten coating taken more concerned on today. So, several difference made tungsten coating technologies was developed, such as, vacuum plasma spray (VPS) physical vapor deposition (PVD), inert gas plasma spray (IPS) and with graded transition interface inert gas plasma spray (IPS- (T)). Some photographs of the cross section of the sample is shown in FIG.3,

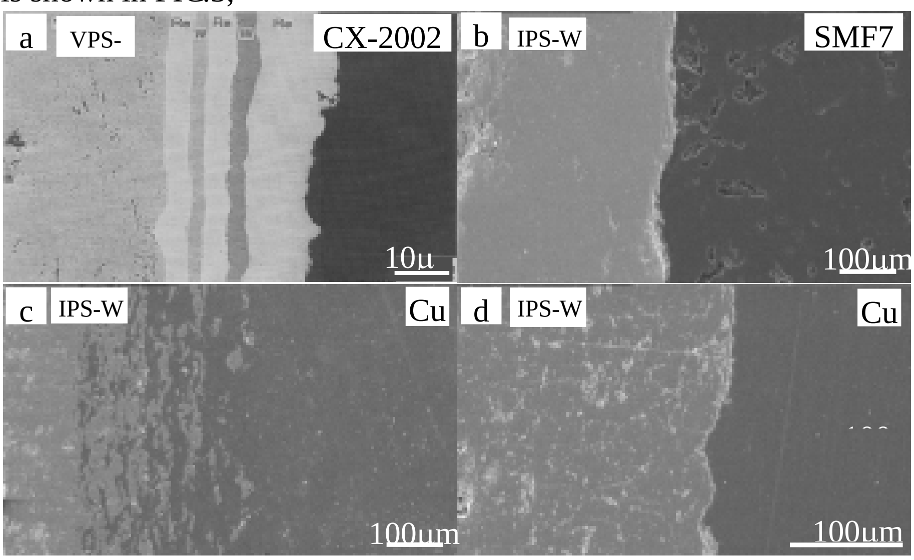


FIG..3. The cross section images of VPS-W/CFC with multi-layer W and Re interface (a), IPS-W coated on SMF700 graphite (b), IPS-W/Cu with graded transition interface (c) and IPS-W/Cu (d) and their high heat flux test (by e-beam) results is indicated in TABLE 2. As comparing one powder metallurgy (PM) sample was used. The results show that vacuum plasma spray (VPS) and with graded transition interface inert gas plasma spray (IPS- (T)) tungsten coating have a better quality than that of made from other methods.

TABLE 2 COMPARED THE HIGH HEAT FLUX TEST RESULT FOR SEVERAL TUNGSTEN COATING

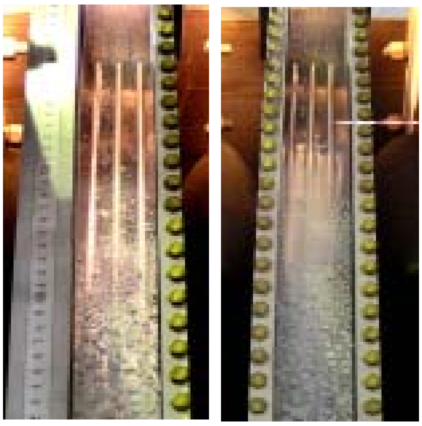
Sample	Heat flux, MW/m^2	Duration, s/s	Cycles, times	Surf. Temp (°C)	Results
PM-W	35	2/30	1000	1150-1250	Recrystallization
VPS-W/CFC	35	2/30	1000	800-950	No damage (Japan)
IPS-W/C	35	2/30	300	500-1600	Failure by detachment
IPS-W/Cu	35	2/30	110	800-900	Failure by detachment
IPS-W/Cu (T)	35	2/30	270	600-700	Failure by detachment
PM-W	85	2/30	60	1800-2000	Recrystallization
VPS-W/CFC	85	2/30	60	1800-2000	No detachment

To understand the interlayer affected on tungsten coating, the anneal effect experiments were performed. The results of heat treatment of IPS-W coatings in a vacuum furnace indicated that most of IPS-W/Cu samples without transition layers failed by the detachment of coating from copper substrate by 900 °C anneal for 4-8 hours, but similar failure was not observed for W/Cu with graded transition interface. Better bonding capability of W/Cu (T) is reasonable since the thermal mismatch of W and Cu has been effectively eliminated by graded transition interface. The X-ray diffraction patterns shows that most of the tungsten coating in the interface turned to W_2C phase by solid reaction of tungsten and carbon by 1200 °C anneal for 2 hours, and almost complete WC structure was found for the case of 1200 °C anneal for 8 hours.

For VPS-W/CFC with W-Re multi-layer sample, the microstructure of multi-layer tungsten and rhenium kept its original structure when the anneal temperature was below 1300 °C, however, the increase of the mixture of W, Re and C at interface was observed with anneal temperature increase. Tungsten carbides were developed at interface while temperature was beyond 1600 °C for1-hour incubation time and the thickness of tungsten carbides rapidly increased with temperature rise. The thickness of the phase reached to 200 μm for the 1800 °C case.

4. Liquid metal free surface MHD stabilities

Liquid metal free surface concept is considered for divertor, limiter and tile of first wall in fusion device because it can withstand over 50 MW/m^2 heating load and be easily renewed by circulation to overcome neutron irradiation damage life time limit. But there are very few available data on theory and experiments, especially experimental data for jet flow magnetohydrodynamic stability. For experiments of liquid metal free surface jet flow in gradient magnetic field, the greatest challenge is how to diagnose the jet flow situation, and for theories, up to now, it is no available that a modeling can well explain MHD phenomenon of a liquid metal jet. Recently, some experiments have been carried out with a visible test unit in LMEL (liquid metal experimental loop, at Southwestern Institute Physics, China) facility, and



B=0 B=1.925T

FIG. 4. Jet flow photo in cases B=0 (left) and B=1.925 T (right), velocity at nozzles is the same for both cases, or v=2.91 m/s

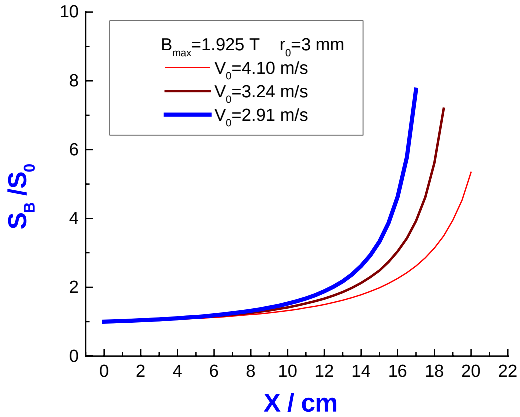


FIG.5 The areas of the cross section of jet flow changes with x from theoretical expect value under difference magnetic field conditions.

one simplification modeling has developed to explain the observed experimental phenomena. Three jets (diameter=6mm) with 60º angle to gravity, go through a gradient magnetic field (0.2 - 1.925 T, the change rate is 14.2 T/m), and one result is shown in FIG. 4. It can be seen that jet run distance (from nozzles to the point of jet touch bottom of test unit) is strength short by the gradient magnetic field, but its surface is smoother than that of in B=0 case. The run distance was 14.4, 15.8, 20.7 and 23.4cm for B_0 equal to 1.925, 1.025, 0.74 Tesla and without magnetic field, respectively. The modeling expectation values are agreed with the experimental data. The cross section of jet flow changed with jet path from the modeling expected is shown in FIG.5.

Acknowledgments

The National Natural Science Foundation Committee (Grand No.B19789503 & B10275019) and the China National Nuclear Corporation supported this research.

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