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2.6 Thermal Shock Tests of Functionally Graded Materials (FGM)

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Key words Functionally graded materials Thermal load Damage mechanism

It is well known that the plasma facing components (PFC) of fusion reactors will be in a harsh environment, and the surface thermal load will reach 5 ~ 10 MW · m^{-2} on the normal operation conditions. When plasma instablility occurred, such as disruption and edge localised modes, the thermal load on PFC will be as high as 100 MW · m^{-2} or more. Therefore, how to design and manufacture PFC and divertor mock-ups is a very important issue. Up to now, the PFCs and divertor mock blocks are made by hot isostatic pressing (HIP), so that a functional medium layer can be formed between plasma facing materials (such as C, Be and W et al.) and thermal sinking materials (such as DS-Cu), which is the superior of functionally graded materials (FGM) . Recent years, FGMs as PFC and divertor components have been developed in cooperation with the Beijing University of Science and Technology. In this paper, properties of FGMs under the thermal load were investigated by simulating the off-normal tokamak operation conditions. The testing materials include B_4C-Cu, W-Cu, SiC-C FGM et al. The heat resource is ND: YAG laser with pulse repeating frequency 10 Hz, pulse length 4 ms, and average power 200 W. The experimental conditions and the damage mechanisms are listed in Table 1. The weight loss rate vs incident power density and cycling number is shown in Fig. 1. Since the samples of SiC/C and SiC were broken under laser shots, their weight loss datum were not obtained.

Fig. 1 shows the relation between weight loss rate (weight loss/area of laser dot) and parameter W, here $W = \Sigma \Phi t^{1/2}$ (kJ · cm^2 · $s^{-1/2}$), Σ is the numbers of laser pulses, Φ is incident flux density (kW · cm^{-2}), t is

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Table 1 Main thermal erosion mechanisms of functionally graded materials

Materials type	Description	Power density /MW · m^{-2} (pulse number)	Erosion mechanisms
Wcu-1	Plasma spraying	123 (200)	Oxidation, no obvious construction damage
Wcu-1(1)	Plasma spraying	123 (350)	Oxidation layers peel off
Wcu-2(1)	Plasma spraying	123 (700)	Re-crystallization, grain boundary thermal stress fracturing
Wcu(90) Wcu 23#, 24#	Hot pressing, Cu infiltration of sintered porosity-graded W skeleton	398 (300)	Evaporation and cracks in the beam dot, chemical decompositon(redeposition) on the edge of the beam dot
BCCU-1-1	Plasma spraying, Ni as for medium	123 (200)	No obvious damage on the surface and section, only oxidation of Cu in surface
BCCU-1-2	Same as BCCU-1-1	398 (100)	Cracks appear at the edge of laser dot, parts of B_4C in the crater were evaporated completely, melting Cu was found. Stress fracturing appears between the B_4C and medium Ni, Ni and Cu matrix
BCCU-1-3	Same as BCCU-1-1	398 (300)	Same as BCCU-2
BCCU-2	Plasma spraying, Cu as for medium layer	398 (100)	Evaporation and melting in the laser dot, many small circular dots come from melting Cu cool down appeared on the edge of the laser dot
SiC/Cu-70	Power sintering	398 (100)	Toroidal and radial cracks appeared on the surface, melting also be found in the dot, free Si appeared on the edge of the laser dot
SiC-B_4C/Cu (71)	Same as SiC/Cu-70	398 (100)	Approximately same as SiC/Cu-70
B_4C/SiC-14	Same as SiC/Cu-70	398 (300)	Thermal stress fracturing toroidally around the dot, inter and intra-granular thermal stress fracturing is seen on the edge of the dot
SiC/C(17)	$\alpha-SiC+B+C$	398 (100)	Broken into several pieces
SiC/C(28)	$\beta-SiC+Y_2O_3+Al_2O_3$	398 (50)	Same as SiC/C(17)
SiC		398 (20)	Same as SiC/C(17)

pulse length. One can notice that the weight loss of FGMs are negative for lower W values, which means the weight of samples increased after laser shocks due to oxidation of metals. With the W value increasing, namely power density or laser pulse numbers increasing, the oxidation layers are removed away in the laser beam dot, the oxidation only appeared on the outer surface of laser beam dot and copper matrix, and parts of tungsten, B_4C

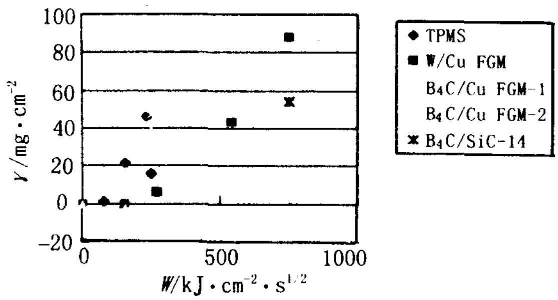

Fig. 1 wight loss rate vs parameter W for high purity graphite and functionally graded materials

or SiC were evaporated and exfoliated in the dot. Therefore, we can measure the weight loss of samples. As comparing, the weight loss rate of high purity graphite TPMS is also listed in Fig. 1. It is obvious that the weight loss rate of W-Cu FGM is lower than that of graphite.

From Table 1, it can be seen that the main damage mechanisms of W-Cu FGM is oxidation layers exfoliation, re-crystallization, grain boundary thermal stress fracturing, evaporation and cracks, chemical decomposition (redeposition) with the increasing of power density. As for B_4C-Cu FGMs, cross section SEM photograph showed cracks and fracturing occureed on the interfaces of the sample with Ni as medium layer under 300 times laser shots with power density 398 MW · m^{-2} and so not for the sample with Cu as medium layer. For SiC samples, SiC and SiC/C with out functional medium show very poor properties, all three samples were broken into several pieces during 20 ~ 100 times laser pulse shots with power density 398 MW · m^{-2}. As a word, FGMS show better capability to withstand high heat loads and integrity under thermal cycling, material synthesis with functional medium layer is a promising method to design and manufacture PFCs and divertor components.

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2.7 The Development of V-based Alloys

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Key words Vanadium alloy Development

Vanadium alloy has the potential advantages over other structural materials for fusion application. It is not only good in high temperature property, high resistance to neutron irradiation and feasibility of fabrication, but also a typically low activation material. However, the alloy is easily contaminative in the process of fabrication at elevated temperature such as hot rolling, causing the loss in ductility and toughness. In this paper, a process was introduced to prepare several kinds of vanadium alloys.

Pure vanadium, titanium metal and chromium were used to prepare the al-