EXPERIMENTAL STUDY OF PLASMA-SURFACE INTERACTION AND MATERIAL DAMAGE RELEVANT TO ITER TYPE I ELMS

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The paper presents experimental investigations of main features of plasma-surface interaction and energy transfer to the material surface in dependence on plasma heat loads. The experiments were performed with QSPA repetitive plasma pulses of the duration of 0.25 ms and the energy density up to 2.5 MJ/m^2. Surface morphology of the targets exposed to QSPA plasma screams is analyzed. Relative contribution of the Lorentz force and plasma pressure gradient to the resulting surface profile is discussed. Development of cracking on the tungsten surface and swelling of the surface are found to be in strong dependence on initial temperature of the target.

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1. INTRODUCTION

The major part of ITER divertor armor is foreseen to be made of tungsten and carbon fibre composite (CFC). Energy loads to ITER divertor surfaces associated with the Type I Edge Localized Modes (ELMs) are supposed to be up to Q = 3 MJ/m^2 during τ = (0.1…0.5) ms and the number of ELMs about 10^3 for one ITER pulse [1].

Quasi-Steady-State Plasma Accelerators (QSPA) well reproduce the energy densities (Q) and pulse durations (τ) of ITER ELMs [2, 3]. Experimental investigations of plasma-surface interaction in ITER relevant conditions are aimed the determination of main erosion mechanisms for the divertor armour materials, dynamics of erosion products, vapor shield effects under plasma heat loads. In turn, the obtained results are used for validation of predictive models developed for ITER [4], estimation of tolerable size of ITER ELMs and lifetime of divertor armour materials.

The paper describes experimental investigations of plasma energy transfer to the material surface in dependence on plasma heat loads. Some results on electromagnetic force influence on the melt motion of metals and effect of preheating on the tungsten damage are presented also.

2. EXPERIMENTAL DEVICE

The samples of different materials (tungsten, copper, titanium, MPG-7 graphite) have been exposed with various number of pulses of hydrogen plasma streams produced by the quasi-steady-state plasma accelerator QSPA Kh-50, described elsewhere [2]. The experiments were performed with repetitive pulses of the duration of 0.25 ms and the energy density in the range of (0.5…2.5) MJ/m^2. The plasma stream diameter is 18 cm, the ion energy is about 0.4 keV, and maximum plasma pressure achieves 3.2 bar.

Molybdenum diaphragms with different diameter of holes were used to form narrow central part of plasma stream, which is impacted on the target surface, and to create situation when target size exceeds the plasma stream diameter. Scheme of target irradiation is described in details in [5]. In some experiments an Ohmic heater was installed behind the tungsten target to study the influence of target preheating up to $t_{init} \approx 650$ °C on surface cracking [6, 7].

Contribution of electromagnetic force to the melt layer erosion of metals was investigated with use of special magnetic system for creation of magnetic field along the exposed surface. The maximal external magnetic field of up to 1.5 T and electric current density of ~1.4 kA/cm^2 through the melt layer are achieved [8].

Calorimetry (both at plasma stream and at the target surface), piezo-detectors, electric and magnetic probes, Rogowski coils, spectroscopy and other diagnostics were applied for measurements of plasma parameters and surface heat loads in different regimes of operation.

3. EXPERIMENTAL RESULTS

3.1. PLASMA ENERGY TRANSFER TO THE MATERIAL SURFACES

As it was shown earlier in disruption simulation experiments [2] the main feature of high-power plasma interaction with material surfaces is dense plasma shield formation in front of the target surface. The ELM heat loads is much less than disruption ones, however, some shielding effect can also appear in this case.

Fig.1. shows the heat loads to the tungsten surface, which were measured with calorimetry, in dependence on energy density of impacting plasma stream for 2 cases: without and with graphite as surrounding surface. For these studies the combined W-C target was prepared. Onset of tungsten melting is observed on the target surface at pulsed heat load of 0.57 MJ/m^2.

For tungsten target the vapor shield formation and its influence on plasma energy transfer to the surface became clearly seen when the surface heat load achieves 1.1 MJ/m^2. Measurements of heat loads for combined tungsten-graphite target show that the value of energy density delivered to the target surface is reduced in comparison with tungsten irradiation. In this case the carbon vapor shield formation results in additional decrease of the surface heat loads up to (0.8…0.85) MJ/m^2.

The measurements demonstrate that even for plasma exposures, which not resulted in tungsten melting, the target heat load is about (55…60) % of the impact plasma energy. The dynamical screening of the surface from impacting plasma stream appears in this case probably due to plasma stream thermalization under the plasma stream interaction with target surface. The layer of stopped plasma formed from head part of the plasma stream becomes not completely transparent for subsequently impacting plasma ions. However the vapor shied formation, especially in the case of mutual neighborhood of carbon and tungsten results in much more pronounced surface screening and essentially restricts the energy transfer to the surface.

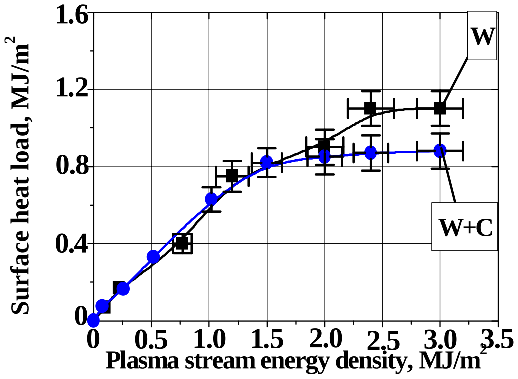

Fig. 1. Heat load to the target surfaces vs. the energy density of impacting plasma stream

The fraction of plasma energy, which is absorbed by the target surface, is rapidly decreased with achieving the evaporation onset for exposed targets. At this, the value of heat load to the surface remains practically constant with further increase of the energy density of impacting plasma (plateau region in Fig.1).

3.2. EXTERNAL FORCES INFLUENCE ON THE MELT LAYER EROSION

The main aim of these experiments was analysis of relative contributions of pressure gradient and the Lorentz force to the resulting erosion profiles

Irradiation of tungsten samples with repetitive plasma heat loads above the melting threshold was performed in conditions of practically constant plasma pressure along the exposed surface, but with additional action of electromagnetic force to the melt layer. Force duration was ~150 µs and maximal magnitude was (14…20) MN/m^3 (time averaged one was ~10 MN/m^3). It is obtained that Lorentz force causes continuous inclination of the surface profile in direction of the force. It contribution to the resulting erosion profile of tungsten is on the level of 2µm after 20 pulses (Fig. 2a).

Relative influence of the Lorentz force and plasma pressure gradient can be easily seen on the profile of Ti target (Fig. 2b), which was exposed through the diaphragm of 3 cm with the aim to impose the pressure gradient at the 5 mm edge zone of the melt spot [5, 8]. The ridge of displaced material with the height of (70…100) µm is arisen locally at the melt edges due to effect of the plasma pressure gradient, which is the main driving force for the peripheral surface regions close to the diaphragm edges.

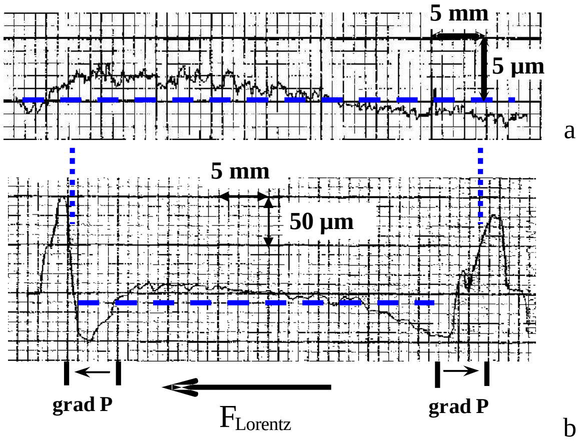

Fig.2. Surface profiles of targets exposed with 20 pulses: a – tungsten; b – titanium

It should be pointed out that for left side of Ti profile, the Lorentz force adds to the melt motion, and for right side it is directed opposite to the pressure gradient. That is why, the ridge height for left side of presented profile is higher. For the same reason the width of the erosion crater at the right side is larger. The inclination of the profile central area is completely determined by Lorentz force action. The displacement of target material according the of the Lorentz force direction resulted in profile grow up to 20 µm for 20 pulses. Areas of predominant action of the plasma pressure gradients and the Lorentz force are marked in Fig. 2. In the central area of exposed surface the Lorentz force is dominating. However, for thin edge regions the value of pressure gradient in 3 times exceeds the magnitude of Lorentz force.

3.3. INFLUENCE OF TARGET PREHEATING ON TUNGSTEN EROSION

Plasma exposures of tungsten targets with initial temperature at RT level resulted in formation of large size cracks and fine inter-granular cracks on the surface (Fig. 3). Surface cracking leads to essentially increased surface roughness of tungsten and swelling of the surface profile as whole according to initial reference line [6]. Microscopy analysis shows growing width of the cracks with increased number of exposures.

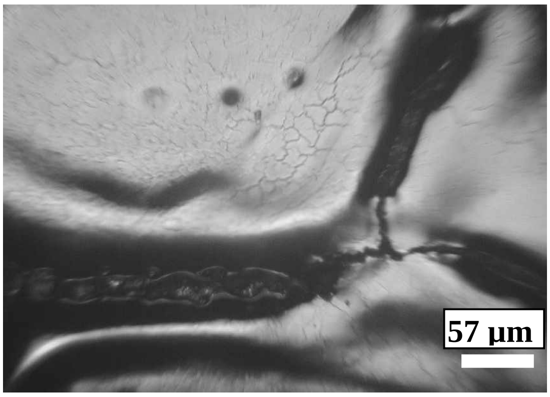

Fig. 3. Cell of crack mesh on tungsten surface after exposed of 100 pulses, t_{init} = RT

For the preheated target surface, the roughness grows up very slowly with increase of irradiation dose. Microscopy studies demonstrate absence of large cracks, while a fine crack mesh is still developing. Width of intergranular cracks increases with number of pulses and achieves 0.8…1.5 μm after 100 pulses. SEM shows development of cellular structure on the resolidified tungsten surface after plasma exposures. Cell size is about 300 nm. Blister-like structures with size up to 100…150 μm are also appear on the surface after large number of exposures (Fig. 4).

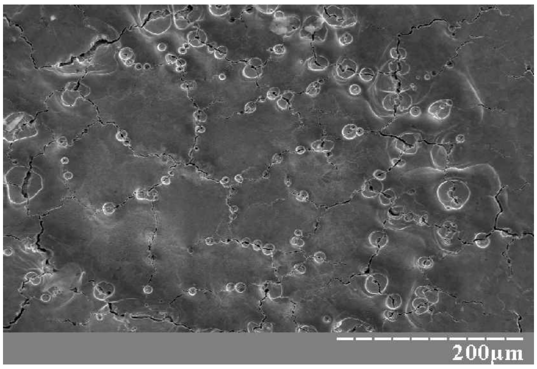

Fig. 4. SEM image of exposed tungsten surface after 100 pulses, t_{init} =650 ºC

4. CONCLUSIONS

The obtained results can be summarized as follows:

- Onset of vapor shied formation in front of the surface under the plasma impact is studied. Achievement of evaporation threshold for exposed targets results in almost saturation of the surface heat load with further increase of the plasma energy density. The investigations of mutual neighborhood of graphite and tungsten showed the reduction of energy delivered to the tungsten surface. In spite of high energy density of impact plasma a tungsten evaporation threshold is not achieved due to the carbon vapor shield formation.
- Relative contribution of the Lorentz force and plasma pressure gradient to the resulting surface profile due to the melt motion is demonstrated.
- Tungsten preheating above DBTT allows suppression of macrocracks formation on the surface. However, the mesh of fine intergranular cracks is steel developed. Taking into account a lot of ELMS during each ITER pulse, the evolution of fine cracks and surface morphology requires additional studies with large number of plasma exposures.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИЗУЧЕНИЕ ВЗАИМОДЕЙСТВИЯ ПЛАЗМЫ С ПОВЕРХНОСТЬЮ И ПОВРЕЖДЕНИЙ МАТЕРИАЛОВ В УСЛОВИЯХ ВОЗДЕЙСТВИЯ ELM ТИПА I В ИТЭРе

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Представлены экспериментальные исследования основных особенностей плазменно-поверхностного взаимодействия, и передачи энергии поверхности материалов в зависимости от плазменных тепловых нагрузок. Эксперименты были выполнены с периодически повторяющимися плазменными импульсами КСПУ длительностью 0,25 мс и плотностью энергии до 2,5 МДж/м^2. Проанализирована морфология поверхностей мишеней, облученных КСПУ плазменными потоками. Обсуждается относительный вклад силы Лоренца и градиента давления плазмы в развитие профиля поверхности. Установлена сильная зависимость развития растрескивания поверхности вольфрама и раздувания поверхности от начальной температуры мишени.

ЕКСПЕРИМЕНТАЛЬНЕ ВИВЧЕННЯ ПЛАЗМОВО-ПОВЕРХНЕВОЇ ВЗАЄМОДІЇ ТА ПОШКОДЖЕНЬ МАТЕРІАЛІВ В УМОВАХ ВПЛИВУ ELM ТИПУ I В ITEPi

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Представлені експериментальні дослідження основних особливостей плазмово-поверхневої взаємодії, і передачі енергії поверхні матеріалів у залежності від плазмових теплових навантажень. Експерименти були виконані з періодично повторюваними плазмовими імпульсами КСПП тривалістю 0,25 мс і густиною енергії до 2,5 МДж/м^2. Проаналізовано морфологію поверхонь мішеней, опромінених КСПП плазмовими потоками. Обговорюється відносний внесок сили Лоренца і градієнта тиску плазми в розвиток профілю поверхні. Установлено сильну залежність розвитку розтріскування поверхні вольфраму і роздування поверхні від початкової температури мішені.