MATERIALS IN CONDITIONS OF HIGH POWER PLASMA LOADS: SURFACE DAMAGE AND MODIFICATION

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The paper discusses main features of material response to the repetitive powerful plasma impacts caused either the damage mechanisms and erosion behaviour or modification of surface layer and alloying with plasma species, aimed at improvement of material performance. Influence of powerful plasma impacts on several materials used for the construction of energy systems, i.e. steels as well as tungsten coatings, and pure tungsten has been discussed.

Introduction, experimental conditions, samples and diagnostics

Simultaneous impacts of high energy and particle loads to the material surface are typical for material performance in various extreme conditions: space apparatus in upper atmosphere, operation of turbines, nuclear engineering, fusion etc [1. 2]. The paper discusses main features of material response to the repetitive powerful plasma impacts caused either the damage mechanisms and erosion behaviour or modification of surface layer and alloying with plasma species, aimed at improvement of material performance.

Surface modifications by powerful pulsed plasma streams were carried out with the use of a QSPA Kh-50 quasi-stationary plasma accelerator [3]. The main parameters of the QSPA hydrogen plasma streams were as follows: ion impact energy was about (0.4…0.6) keV, the maximum plasma pressure reached up to 0.32 MPa, and the plasma stream diameter was about 18 cm. The surface energy load measured with a calorimeter was varied between melting (0.6 MJ/m^2) and evaporation (1.1 MJ/m^2) thresholds. The load pulse shape was approximately triangular, and the pulse duration was 0.25 ms [3, 4]. Pure tungsten target has been manufactured from sintered tungsten material of Plansee AG trademark with sizes of 5 × 5 × 1 cm with slits. The size of each target unit is 24x12x5 mm, that is comparable to momoblocks in ITER. The width of gaps between elements is 1 mm. The surface of the target was oriented perpendicularly to the impact plasma stream. The target temperature before and between irradiating pulses corresponded to room temperature level. The maximum number of plasma impacts achieved 200 pulses. The samples made of the Eurofer alloy (Cr-9.7%, Mn-0.7%, Fe-89.6%) were also irradiated by QSPA plasma streams. All the samples had the size of 10×10×0.5 mm^3. These samples were covered by tungsten coatings of about 3 μm in thickness, which were deposited with a PVD technique [5] within a Bulat-type facility. Earlier such coatings were applied for estimations of their performance as plasma-facing surfaces (in a comparison with monolithic tungsten targets). They enabled also an analysis of the adhesion properties of the PVD coatings, and an investigation of the plasma-facing components prospective for the reactor first wall construction [3]. The energy density in free plasma and the surface heat loads were measured by means of the local calorimeters. Observations of plasma interactions with the exposed surfaces were performed with a high-speed 10-bit CMOS pco.1200s digital camera of the PCO AG type (in the spectral range from 290 nm to 1100 nm, with an exposure time ranging from 1 μs to 1 s) [3, 4, 6]. The surface analysis of the exposed samples was carried out with a MMR-4 optical microscope, equipped with a CCD camera. There were also performed measurements of weight losses, as well as precise measurements of the surface roughness with a Hommelwerke T500 tester. To study a micro-structural evolution and contents of elements and phases in the exposed targets, the x-ray diffraction technique (XRD) was applied [7]

Results and discussion

The most important results of these studies can be summarized as follows. Repetitive plasma loads above the melting tungsten threshold led to formation of melted and resolidified surface layers [3,4]. Networks both macro and intergranular cracks appeared on exposed surfaces. Cracks propagate to the bulk mainly transversely to the irradiated surface. The splashing of tungsten dust/liquid particles has been analyzed in the course of repetitive plasma pulses. It was revealed that mountains of displaced material at the edges of castellated units are primary source of the splashed droplets due to development of instabilities in melted layer [6]. The solid dust ejection dominates by cracking processes after the end of pulse and surface resolidification. Due to the continuously growing crack width (from value of sub-μm till tens μm) with increasing number of pulses the initially uniform melt pool on the castellated units became disintegrated into a set of melt structures separated by cracks. After large number of exposures, the progressive corrugation of the surface occurred due to the capillary effects on exposed tungsten surfaces. Results of simulation experiments for castellated targets and developed surface structures are compared with repetitive plasma exposures of flat tungsten surfaces.

Experimental research on surface modifications of stainless-steel grade was performed. These SS-grades are a possible options as plasma-facing materials of the DEMO-reactor first wall. The samples of Eurofer (Cr-9.7%, Mn-%0.4, Fe-89.6%) ferritic/martensitic-steels covered by tungsten coatings were treated within the powerful plasma streams [8]. The preliminary tungsten coatings were deposited by a PVD method. Possibility of the alloying of SS-surfaces with tungsten coatings was demonstrated. An increase in the tungsten concentration was observed. The tungsten phase was identified together with some lines of the Fe phase upon the treated surfaces. The presence of the α-Fe phase created good conditions for the tungsten penetration into the affected layer. The tungsten concentration achieved several wt% in the surface layer of thickness up to 4 μm. Symmetrical tensile stresses up to 270 MPa were recorded in the near surface layer. As a result of the stresses development, some delamination of the coatings during the pulsed plasma irradiation was observed. The surface morphology was changed mostly by the melting and re-solidification of a surface layer. Macro- and micro-cracks appeared also on the modified surfaces.

Summary

Broad combination of mechanisms of powerful plasma influence on material properties includes not only the surface damage due to the different erosion mechanisms but also significant improvement material properties in surface layer, its structure and substructure due to high-speed quenching, shock wave formation, material alloying with plasma impurities. Fast heating and melting of the treated surface, giving rise to considerable temperature gradients ($\sim 10^6$ K/cm) in the surface layer of material under the pulsed plasma impact. This contributes to high speed diffusion of plasma stream ions into the depth of the modified layer, resulting in phase changes in the surface layer and the formation in the course of subsequent fast resolidification the fine-grained or quasi-amorphous structures.

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