

## Study of tungsten at multiple ELM-power loads

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Tungsten is considered as basic material for protection of the ITER divertor from large thermal loads. It is likely that the surface will occur many times melting and solidification during the transient events (current disruption or local instabilities) leading to a sharp increase in heat flows. These events may give to formation of thin fragile surface layer due to the effects of multiple crystallization. Molten and modified layer may arise on the tungsten coating surface to a depth of 200  $\mu\text{m}$ . Further interaction of this layer with plasma may possibly cause portions of detaching of the layer with “flakes” leading to disruption of current through the plasma. It is assumed that during one discharge the surface layer can be remelted up to 1000 times in divertor of ITER. This work is aimed at experimental study of cyclic plasma effect on tungsten elements developing for ITER. Investigation of structure and properties of tungsten surface layers modified under irradiation at multiple ELM - events and their subsequent exposure in deuterium plasma of the tokamak Globus-M were performed. Two types of ITER-like tungsten (JSC POLEMA and PLANSEE Double Forged) were investigated. Study of cyclic plasma-tungsten interaction was conducted at the plasma gun test bench [1] and tokamak Globus-M [2]. Heat flux factor  $\varepsilon$  is utilised for comparison transient heat loads generated by different sources [3]. For ELM-event in ITER  $\varepsilon_{\text{ELM}} = 77 - 123 \text{ MJ m}^{-2} \text{s}^{-1/2}$ , for plasma jet of the gun  $\varepsilon_{\text{gun}} \leq 300$ , for tokamak Globus-M  $\varepsilon_{\text{Globus-M}} \sim 1$ , melting of tungsten  $\varepsilon_{\text{melt W}} \sim 48$ . Plasma jet generated in cyclic mode (up to 200 shots during working day) providing multiple remelting of tungsten. Jet parameters were the following: heat flux  $1 \text{ MJ/m}^2$  ( $100 \text{ GW/m}^2$ ), time duration of pulse  $15 \mu\text{s}$ , plasma density  $(0.5-5) \times 10^{22} \text{ m}^{-3}$ , number of the accelerated particles  $(1-5) \times 10^{19}$ , jet velocity  $100-200 \text{ km/s}$  [4]. In few days the gun allowed getting material damage close to the condition in fusion reactor. Samples were irradiated at energy density  $\sim 0.8 \text{ MJ/m}^2$  and  $\varepsilon = 230 \text{ MJ m}^{-2} \text{s}^{-1/2}$ . Scanning electron microscopy (LEO 430, Japan) was used for investigation of irradiated surfaces.

Video (Optronis CR Series) and infrared (Flir SC 7300M MWR MCT) cameras observed diverter region of the tokamak Globus-M.

As was shown in works [5,6] few cycle jet impact changes the nature of the surface layer of JSC POLEMA tungsten. After five cycles the melted layer with depth 3 - 6  $\mu\text{m}$  having a wave relief was formed. Many cycle irradiations changed the nature of the irradiated surface even more (Fig.1). After 150 pulses sharply expressed "hole-peak" wave surface was observed. Character of surface showed that tungsten was in the melted state. Developed surface had net of the microcracks resulted by thermal tension at material cooling with a high speed. After 1000 pulses formation of drop-dendrite structure on rather flat plateau was observed. The structure was also penetrated by net of microcracks. Depth of the damaged layer after 100 and 1000 shots of irradiation was clearly visible on polished cut of the irradiated samples (Fig.2). In the first case a friable "hole-peak" structure with amplitude of 60-70  $\mu\text{m}$  was observed. After 1000 shots the "hole-peak" structure disappeared. There was a smoothed relief of the moved melted and stiffened metal at a depth up to 90  $\mu\text{m}$ . Thus multiple irradiations changed the mechanism of destruction of the irradiated tungsten. Great loosened "ridges" melted with creation so-called "welded" surface and the drop structures were created. These drops in course of irradiation can come off a surface in the melted state and again settle on it.

The surfaces structures of PLANSEE Double Forged tungsten after 100 and 1000 shots of irradiation also as in case of tungsten JSC POLEMA were considerably differed (Fig. 3). In the first case irradiation formed a surface with existence of the "bobbin" structures located practically perpendicular to the plane of irradiation. After 1000 cycles the surface was greatly hardened because of repeated melting. Spatial elements of structure became wider. The structure got a form of roughly melted metal as well as in case of JSC POLEMA tungsten after

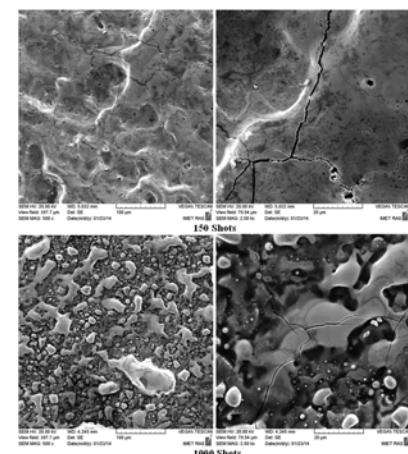


Fig.1: Surface of JSC POLEMA tungsten after cyclical irradiation

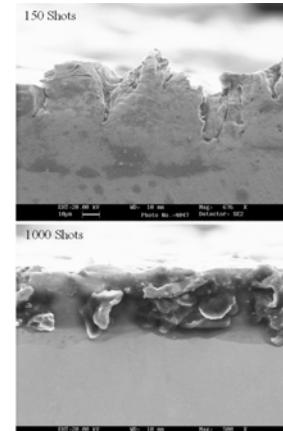


Fig.2: Microstructure of JSC POLEMA tungsten on polished cut of sample

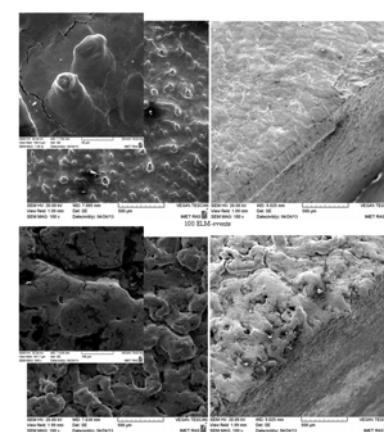


Fig.3: Surface of PLANSEE Double Forged tungsten after cyclical irradiation

1000 shots. The polished cut layer at 100 cycles showed the wedge-shaped cracks going from the irradiated surface into material and forming friable layer under irradiated surface (Fig.4a,b,c). Depth of cracks was about 30  $\mu\text{m}$ . Apparently their location was connected with borders of the blocks coming to irradiated surface. Shift strips and areas of loosening of the material confirming probably about dispatch - wave impact on material was observed. The increase in number of shots to 1000 leaded to expansion of area of cracks and formation of loose coating along irradiated surface at a depth of 100-200  $\mu\text{m}$  (Fig.4d,e,f). The obtained results are in good agreement with the data presented by number of researches using other plasma sources; in particular devices of plasma focus [7-9].

Tiles of 4 kinds of tungsten previously irradiated in different conditions were placed in the region of the Globus-M divertor (Fig.5). Tiles were irradiated in deuterium plasma at 2068 shots (sum exposition  $\sim 150$  s). No visible changes in plasma parameters were observed. Video camera showed radiation at outer branch of separatrix independently of material and type of preliminary irradiation (Fig.6). But infrared camera showed non-uniform temperature field at the tiles (Fig.7). Surface temperature of JSC POLEMA tungsten pre-irradiated with 1000 jet cycles increased in comparison with surface temperature both non-irradiated and irradiated with 100 jet cycles and 1000, 2000 electron beam cycles. Temperature of the spot irradiated with jet was higher than temperature of the surface damaged with electron beam. Possibly the loose layer created by jet interfered with heat removal from surface to tile depth. It is likely that surface remelted by electron beam didn't lead to formation of the recrystallized layer. Temperature of PLANSEE Double Forged tungsten previously irradiated by plasma jet with 100 and 1000-ELM-events increased in comparison with the non-irradiated tungsten tiles. Surface temperature of the damaged tungsten increased in comparison with surface temperature of graphite tiles.

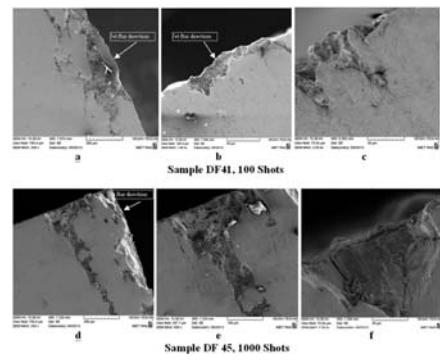


Fig.4: Microstructure of PLANSEE Double Forged tungsten on polished cut of sample



Fig.5: Arranging the divertor with tiles of different kinds

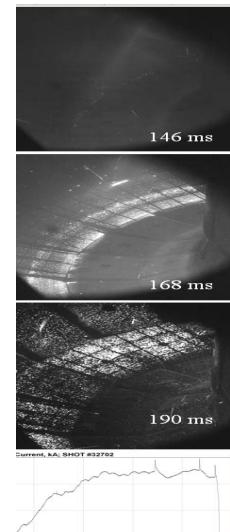


Fig.6: Video frames of the Globus-M divertor. Shot 32702

## Summary

Results of multiple impact of plasma on tungsten elements of JSC POLEMA and PLANSEE Double Forged types are presented. The structure and morphology of repeatedly melted layer after irradiation with the energy equivalent to ELM-events was studied. Considerable changes of layer after cyclical irradiation were found. After 100-fold irradiation the "hole-peak" structure of the loosened metal was formed. 1000-fold irradiation changed character of topography considerably. The distinguished "ridges" were melted with formation of drop structures. The surface became rough. The wedge-shaped cracks going from the irradiated surface deep into material was observed. The loose coating under irradiated surface was formed. The recrystallized layer up to depth  $\sim 100$   $\mu\text{m}$  was obtained. Tiles of different kinds and pre-irradiated at different conditions were installed and investigated in the divertor region of the tokamak Globus-M. Non-uniform temperature field on pre-irradiated samples after discharge disruption was registered. Surface temperature of previously irradiated PLANSEE Double Forged tungsten at 100 and 1000-ELM-events exceeded the temperature of non-irradiated sample. Surface temperature of preliminary irradiated JSC POLEMA tungsten at 1000-ELM-events exceeded the temperatures registered in other tiles. No visible changes in discharge behavior of the tokamak Globus-M equipped with tungsten tiles were observed.

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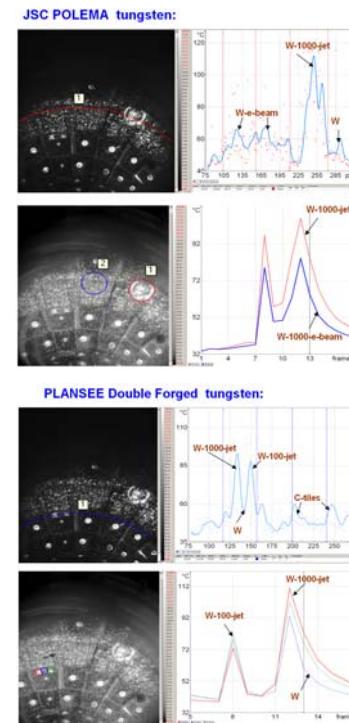


Fig.7: Infrared image of the Globus-M divertor. Shot 32702