Plasma flow interaction with ITER divertor related surfaces

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Abstract. It has been found that the plasma flow generated by quasistationary plasma accelerators can be used for simulation of high energy plasma interaction with different materials of interest for fusion experiments. It is especially important for the studies of the processes such as ELMs (edge localized modes), plasma disruptions and VDEs (vertical displacement events), during which a significant part of the confined hot plasma is lost from the core to the SOL (scrape off layer) enveloping the core region. Experiments using plasma guns have been used to assess erosion from disruptions and ELMs. Namely, in this experiment modification of different targets, like tungsten, molybdenum, CFC and silicon single crystal surface by the action of hydrogen and nitrogen quasistationary compression plasma flow (CPF) generated by magnetoplasma compressor (MPC) has been studied. MPC plasma flow with standard parameters (1 MJ/m$^2$ in 0.1 ms) can be used for simulation of transient peak thermal loads during Type I ELMs and disruptions. Analysis of the targets erosion, brittle destruction, melting processes, and dust formation has been performed. These surface phenomena are results of specific conditions during CPF interaction with target surface. The investigations are related to the fundamental aspects of high energy plasma flow interaction with different material of interest for fusion. One of the purposes is a study of competition between melting and cleavage of treated solid surface. The other is investigation of plasma interaction with first wall and divertor component materials related to the ITER experiment.

1. Introduction
Intense thermal loads in fusion devices which occur during ELMs (edge localized modes), plasma disruptions and VDEs (vertical displacement events), will result in macroscopic erosion associated with the formation of cracks, melting, droplets, evaporation or sublimation. The main goals of plasma surface interaction investigation are simulation the expected ELM and disruption loads in ITER and other fusion devices [1].

Edge localized modes (ELMs) represents sudden bursts of particles and energy out of the plasma due to turbulent transport processes localized in the tokamak edge region. Peak heat loads on the divertor plates and first wall during ELMs. The ELMs occurring during ELMy H-mode called Type I ELMs lead to the largest particle and power fluxes onto the divertor plates and expel from the core plasma about 30% of the input power [2].

Power losses are such that the target surface temperature exceeds the sublimation point (for carbon) or melting point (for tungsten). ITER ELMs loads are estimated as (1-2) MJ/m$^2$ during (0.1-1) ms and the repetition frequency of an order of 1 Hz (~400 ELMs during each ITER pulse) [1,2]. The divertor peak power flux during ELMs is in the range of 1-10 GW/m$^2$. For the disruptions, the heat loads to ITER divertor components are anticipated to be of the order (10-100) MJ/m$^2$ with load duration (1-10) ms.
Simulation experiments are being made at pulsed plasma gun facilities such as MK-200, VIKA, QSPA TRINITI [3], QSPA Kh50, PLADIS, as well as at electron beam facilities like JUDITH and JEBIS. The basic idea is an investigation of erosion effects under realistic plasma parameters and conditions. In plasma gun experiments energy loads characteristics of Type I ELMs and disruptions in ITER are obtained and studied. The QSPA facility provides realistic heat loads (i.e., adequate pulse duration and energy density) to simulate the expected Type I ELM loads in ITER [2].

Plasma facing materials for ITER is limited to three basic elements: carbon, beryllium and tungsten. During transient events brittle destruction (carbon based materials) as well as melt layer splashing (metals) can occurs [4]. Maximum allowable ELM energy density is 0.22-0.64 MJ/m$^2$ for carbon and 0.54-1.6 MJ/m$^2$ for tungsten.

The aim of this paper is to present some results from the study of compression plasma flow (CPF) interaction with a targets, in order to demonstrate the capability of CPF from the magnetoplasma compressor to study the materials surface characteristics of interest for fusion devices. During surface treatment by high-power energy beams different phenomena can occur such as evaporation, sputtering, ablation [5], etching [6], exfoliation etc. The material may be removed from surface in the form of charged particles, vapor, liquid droplets, solid flakes etc.

These investigations are related to fundamental aspects of high energy plasma flow interaction with target surface. One of the purposes is observation of competition between melting and cleavage of treated surface. The other is investigation of plasma interaction with first wall component materials related to the ITER experiment.

2. Experimental setup and procedure
A magnetoplasma compressor (MPC) is a source of supersonic CPF and represents a magnetoplasma analog of a Laval nozzle. The electrode system of MPC consists of the conically shaped copper central electrode (cathode) and cylindrical outer electrode made of 8 copper rods, symmetrically positioned along a circle of 5 cm in diameter. In the MPC inter-electrode region the plasma is accelerated due to the Ampere force as the result of the radial component of plasma current $I_r$ interaction with azimuth magnetic field $B_\phi$ (Fig.1). The MPC can operate with different working gases and their mixtures [7,8]. The MPC is a quasistationary system, since the time duration of the CPF is much longer (~50 $\mu$s) than the characteristic flight time of plasma along the accelerating channel (~1 $\mu$s). With hydrogen as working gas and voltage 3-4 kV, typical plasma current is 80-100 kA, discharge duration 100-150 $\mu$s, average plasma density $5\times10^{16}$ cm$^{-3}$, plasma flow velocity up to 120 km/s.

![Figure 1. Scheme of experimental setup: (1) Magnetoplasma compressor (MPC), source of quasistationary compression plasma flow, (2) compression plasma flow, (3) sample, (4) sample brass holder.](image-url)

MPC plasma flow parameters, i.e. plasma energy density ~1 MJ/m$^2$ in 0.1 ms, simulated transient peak thermal loads during Type I ELMs.

For the studies of CPF interaction with surfaces, silicon wafers (100 and 111 orientation) 1 mm thick and 10 mm in diameter, tungsten, molybdenum and CFC were used. The sample is mounted on
the cylindrical brass holder of the same diameter, and placed in front of the MPC cathode at the
distance of 5 cm. The samples are exposed to a single plasma pulse. To investigate the morphology of
treated surface, optical microscopy (OM), scanning electron microscopy (SEM JEOL 840A) and
atomic force microscopy (AFM, AutoProbe CP-Research SPM made by TM Microscope-Veeco) were
used.

3. Experimental results and discussion
OM micrographs of central part of the treated Si (111) and Si (100) surfaces are given in Fig. 2a and
Fig. 2b, respectively. Rhombic and triangular regular fracture features are obtained in the case of Si
(111) (Fig. 2a), as expected for threefold symmetry. On Si (100) surface treated by CPF, two sets of
fracture lines intersecting at 90º form a grid that divides the surface into rectangular blocks (Fig. 2b).
Some of the blocks are ejected from the surface, and large holes at the surface can be seen to emerge.
In this case, development of subsurface fracture, parallel to the surface, occurs. The thickness of this
block is about 10 µm.

![Figure 2. OM micrograph of Si (111) (left) and Si (100) (right) surface after CPF treatment,
central part of the sample. Image size: 50 × 50 µm².](image)

Surface fracture and highly-oriented periodic cylindrical structures [9-11] obtained by single
plasma pulse treatment of the Si (100) sample surface are shown in Fig. 3 and the carbon fibre
components (CFCs) after CPF action are shown in Fig. 4. These silicon structures are obtained in the
peripheral part of the target surface. The obtained periodic cylindrical structures are frozen capillary
surface waves quenched at a particular moment during a process of the melt resolidification [11].
Typical wavelength (hill-to-hill distance) of these ripple structures formed on the treated silicon
surfaces are about 3-4 µm with amplitude (half-distance of hill to valley) of 0.2 µm and lengths up to
200 µm. AFM was used for periodic structures surface investigation. Structures are smooth and
sinusoidally shaped with an amplitude (half hill-to-valley distance) of about 0.3 µm. The regular
silicon surface structures can be obtained on the area region up to several square millimetres. The
estimated average surface temperature was about 2300 K [12].

Formation of the observed surface features may be explained by energetic action of CPF on the
surface. Time evolution of the compression plasma flow interaction with treated silicon sample is
studied using IMACON 790 high speed camera [9]. Analyzing these results, one can conclude that the
interaction of CPF with silicon sample surface causes an evaporation of a thin surface layer and
formation of a shock-compressed plasma layer (plasma plume) [9]. The plasma produced within the
layer consists predominantly of evaporated silicon from the sample surface. Formation of this cloud of
dense target plasma results in the shielding of the processed surface from a direct action of the CPF
and the surface protection from further excessive evaporation. A typical thickness of the shock-
compressed plasma layer is about 1 cm. Using the high speed camera, the time of interaction was estimated to be ~40 µs [9].

![Figure 3. SEM micrograph of Si (100) surface after CPF treatment.](image)

Energetic action of CPF (absorbed energy 10-15 J per pulse, flow power density ~1\times10^5 W/cm² [13]) on the surface causes the fast heating and melting of the surface layer and the presence of high dynamic pressure of CPF of the order of several atmospheres [13]. Namely, CPF kinetic energy thermalization causes the heating of shock-compressed plasma layer. The target surface is heated by convective and radiative heating and a high temperature gradient occurs. In addition, deceleration of the CPF results in the formation of current loops (vortices), due to freezing of the magnetic field into the plasma, and a magnetic field of 1-10 mT is induced at the surface [13].

![Figure 4. The carbon fibre components (CFCs) after CPF action.](image)

Melt layer erosion at high heat loads is melt splashing due to the formation, growth, and bursting of bubbles inside the liquid layer (Figs. 5-7). This results from the continuous heating and overheating of the liquid layer during energy deposition.
Melting of target surfaces during high-power pulsed energy streams treatment is the normally expected effect, but only in some cases are cracks and fractures formed (Figs 2-4). In this experiment, during plasma flow treatment of silicon single crystal surfaces, melting occurs predominantly in the peripheral part of the target. In this region capillary waves are induced on the liquid silicon surface in contrast to the central part of the treated silicon sample where regular fracture features are observed. It is worth emphasizing that regular fracture features formation is a process in competition with surface melting. However, in the surface transition region, both frozen capillary waves and regular fractures are observed.

Figure 5. The large holes formation on silicon surface after CPF action.

Figure 6. The tungsten surface after CPF action (up) and EDAX spectrum (down).
Formation of regular fracture features (Figs. 2 and 3) can be explained by assuming that a considerable fraction of the absorbed plasma flow energy is trapped in fractures rather than converted to heat energy. Single crystal silicon is well known as a typical anisotropic material exhibiting brittle behaviour at room temperature which can be observed as the local response of an atomically sharp crack for a critical loading condition. Covalent bonding in silicon gives rise to a high barrier to dislocation motion and silicon is, therefore, inherently brittle. Silicon single crystal becomes ductile above about 600°C (the brittle-ductile transition), depending on strain rate [14].

The anisotropy of crack propagation direction from an energetic point of view is explained with the Griffith criterion [15]: in equilibrium, the mechanical energy released upon crack advance must be in balance with the energy required to create the two new surfaces. This is a necessary condition for fracture and leads to conclusion that crystal lattice planes with low surface energies are energetically favored as cleavage planes. The lowest energy cleavage planes in silicon are the \{111\} planes [16]. Silicon has two principal cleavage planes: \{111\} planes, usually the easy cleavage planes, and \{110\} planes.

Figure 7. The molybdenum surface after CPF action (up) and EDAX spectrum (down).

Low adhesion between blocks and silicon bulk, and eventual ejection of blocks from the CPF treated surface (Fig. 2), can be explained by the development of subsurface fracture, parallel to the surface. Cracking between the block and the bulk is growing due to local energy absorption. This exfoliation phenomenon is very important for investigation of the plasma interaction with fusion reactor first wall materials, in order to find the conditions for avoiding of high target mass losses.
Detected silicon periodic cylindrical structures obtained in this experiment by interaction of CPF with the silicon surface (Fig. 3) may be presumed as capillary waves [9-11]. Capillary waves on the molten silicon surface are induced during the interaction of the plasma flow with the target. Once the plasma flow interaction with the silicon sample has ended, fast recrystallisation and quenching causes the freezing of wavy structures on the silicon surface. Rapid solidification can produce serious cracking problems due to differential stresses. During cooling and unloading of the treated surface, the residual stresses created in the subsurface region can produce surface fracturing. From Fig. 3 one can conclude that cracking occurred after solidification of periodic cylindrical structures and may be explained with the emerging of residual stresses. Brittle destruction might increase with the number of plasma discharges because of crack propagation into the depth of the sample thus resulting in material pre-damaging. The holes arise because of crack formation resulting in macroscopic destruction.

Melting and thus melt motion, as well as melt layer splashing are expected to be the main mechanisms of metallic target damage. Melt splashing occurs from boiling and gas bubbles, splashing due to absorption of plasma momentum, erosion from hydrodynamic instabilities developed in the liquid layer due to the tangential and perpendicular forces acting on the free surface of the liquid, erosion due to run-off of melt layers over the structure, and erosion caused by mechanical vibration of the machine during the disruption event. These effects are detected at the silicon surface. The plasma stream causes melt layer boiling. Pressure of the impacting plasma stream is 10 atm in the beginning, but with decreasing pressure, violent boiling and bubble formation in the overheated liquid occurs. Bubbles caused large particle emission. The majority of droplets remain at the sample surface.

4. Conclusions
From the surface structures studied here (regular fracture features, frozen capillary waves, bubble formations), it is possible to conclude that they are similar to those originating from macroscopic erosion processes observed for the first wall and divertor surface in fusion devices (predominantly, brittle destruction, melt formation with melt layer splashing, bubbling with large particle emission) [1-4]. Material in the form of droplets and grains was observed as being ejected from surfaces treated by compression plasma flow. This is the evidence that evaporation process plays only a minor role in the resulting surface erosion. The results obtained here verify the capability of compression plasma flow in study of plasma wall interaction in fusion devices with use of different materials in wall construction.

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