Erosion of plasma facing components by arcing at ASDEX Upgrade

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The plasma facing components (PFCs) in a future fusion device has to meet several requirements. A low yield for physical and chemical erosion will allow long live time and reduces the contamination of the plasma. A high melting temperature and high heat conductivity is needed to withstand the power input from the plasma. Additionally manufacturing and costs issues have to be taken into account. In this contribution the possible contribution of arcs, which are observed in all major tokamak experiments, on the erosion of PFCs is discussed. Commonly the material released by arcing is assumed to be insignificant in comparison to physical sputtering and chemical erosion. Recent investigations with metallic PFCs at the inner divertor baffle region of ASDEX Upgrade (AUG) show that locally arcing can be the dominant erosion meachanism[1]. Differently to the sputter process, a significant amount of material is released during arcing as droplets, i.e. spheres of a typical size of some microns. For tungsten it was found that a significant fraction of the dust collected in AUG consists out of these droplets [2]. In the literature erosion by arcs

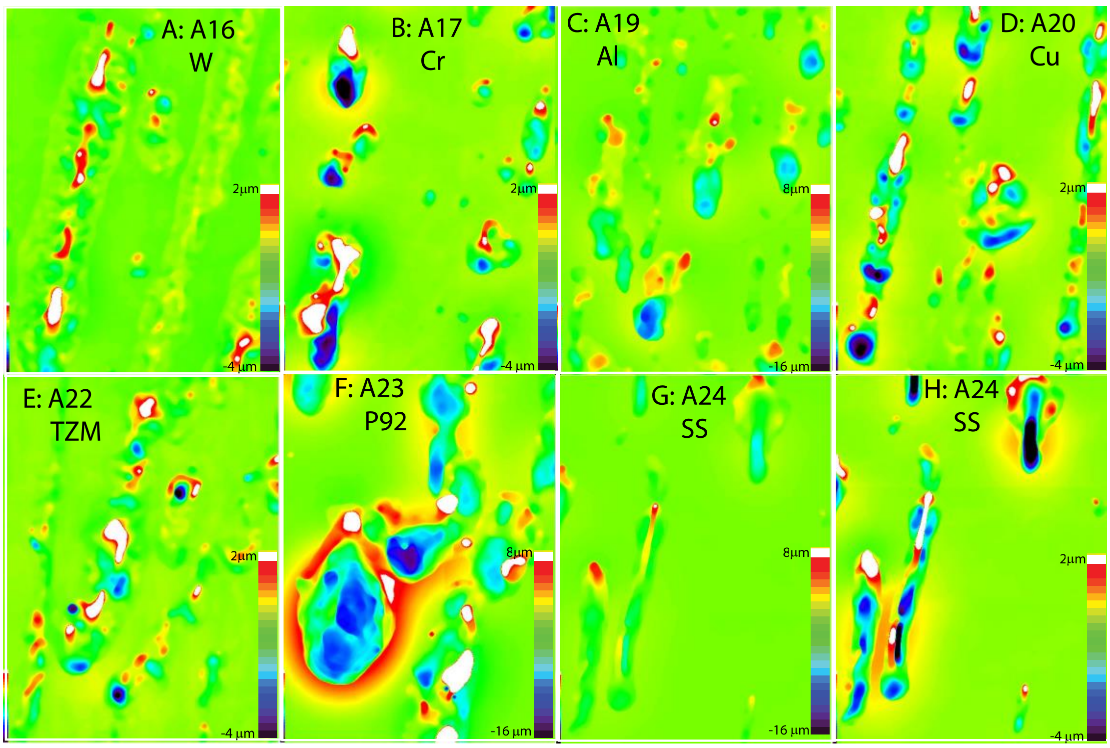

Figure 1: Depth profiles of the materials used. An area of $380*504\ \mu m^2$ is shown. The depth scales are adopted for each material.

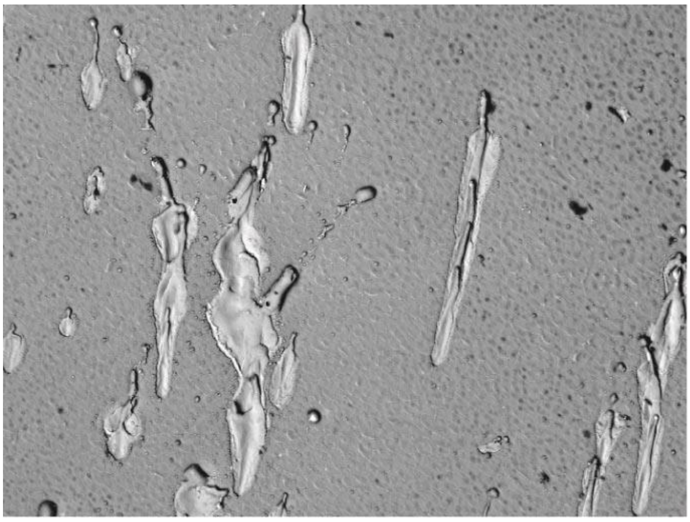

Figure 2: Arc traces on the stainless steel insert. Multiple melting at the same location is observed.

is mostly investigated without or with magnetic fields perpendicular to the surface. In fusion devices the magnetic field lines hit the PFCs under a shallow angle. This may influence the release of molten material, i.e. the production of droplets.

The onset of arcing is a non-linear phenomenon, which seems to be correlated with the occurrence of changes in the SOL during ELMs [3]. The present knowledge of the local plasma parameter does not yet allow simulating this phenomenon so an experimental approach was selected to investigate further effects of arcing.

First investigations compared the PFCs used in AUG: W and magnetic steel P92. Whereas for tungsten the arc traces show only craters up to 4 μm depth, P92 is found to be eroded down to a depth of 80 μm. On average, arc erosion of P92 is about 65 times higher than the one measured for tungsten at the same location [1]. This is in contrast to laboratory data on the erosion by arcs showing only 1.9 times higher erosion of iron compared to W [4].

To investigate arc erosion under fusion relevant conditions, materials with different thermal properties and melting temperatures (Al, Cu, Cr, TZM, W, magnetic (P92) and non magnetic steel (SS)) have been exposed to AUG plasmas at the inner divertor baffle region, which is prone for arcing. Polished inserts were used to avoid grinding grooves from machining allowing an easier identification of arcs tracks. The inserts were mounted in AUG during the experimental campaign 2015/16 comprising 1935 plasma discharges. As the inner divertor baffle region is deposition dominated, the inserts were partly covered with deposits consisting of C, B, W, and O. For analysis a part of the insert was cleaned by wet wiping, only some deposits remain in the arc traces, which may lead to an underestimation of the material eroded. Depth maps were determined using a confocal laser scanning microscope, with offers a spatial resolution of 0.6 μm^2. Typical depth maps obtained by laser profilometry are shown in Fig. 1 for the different materials used.

On all materials traces of arcing are observed. Two different signatures appear: small isolated spots and long traces, which are almost orientated perpendicular to the magnetic field direction. The size of these signatures and especially the depth of the crates vary strongly for the different materials. Some insight in the formation of the arc traces are given by scanning electron microscopy pictures as shown in Fig. 2. Here the non-cleaned part of the insert, consisting of stainless steel, is investigated. The solidified molten material shows some overlap: obviously the same location is molten many times by different arcs. Subsequent arcs are ignited with a higher probability at the location of previous arc traces. By this mechanism existing traces develop to longer lines. The influence of this mechanism on the long term behavior of arcs is unclear, but may lead to an increase of erosion by arcing during the life time. Additionally some droplets, originated by the molten material of the arcs are visible.

Depth maps of 11 areas of a size of 1.9x3.8 mm^2 were analysed. To characterize the erosion of the different materials histograms from the maps were calculated and the affected areas for different depth were integrated. This evaluation reveals a strong local variation of the erosion even on a single sample. To avoid edge erosion the surface of the inserts was mounted retracted some 0.1 mm. The typical angle of incidence of a few degrees causes shadowing on the insert edges and a variation of the deposits found on the insert. Strong erosion by arcing is correlated with the occurrence of deposited layers, i.e. clean surfaces show significant shallower arc craters.

The depth profiles of the areal fraction affected by arcing obtained at a typical, deposition dominated position of each insert are shown in Fig.3a. A magnification of the region close to the surface is added in Fig. 3b. The strongest erosion is observed for the P92 material, which shows craters down to 80 µm. Non-magnetic stainless steel (SS), which has almost the same physical properties, shows much less erosion. Obviously the local modification of the magnetic field angle due to the permeability of the material enhances the erosion. The local modification of the magnetic field is confirmed by the orientation of the arc traces and the profiles across the insert. Below P92 data are not discussed in the comparison of the physical properties. A typical feature for all materials is the hump of the depth profile at depth of about 0.4 µm. Strong erosion by arcing occurs if the arc causes melting of the material. Molten material will be mobilized as droplets, accelerated by the current of the arc and ejected material. The minimum depth for this seems to be similar for all materials. This hump can be used to define the total area, which is affected by the arcing. As simple evaluation yields arc erosion for 7-26 % of the total surface for different materials used. The maximum depth for the traces varies with the materials as summarized in the table below:

Probe	A16-4	A17-11	A19-10	A20-8	A22-4	A24-10
Material	W	Cr	Al	Cu	TZM	SS
Depth [µm]	-3.5	-7.5	-15	-10	-17	-11
Erosion at 0.4µm [%]	12.7	16.7	14.5	15.3	26.0	6.8

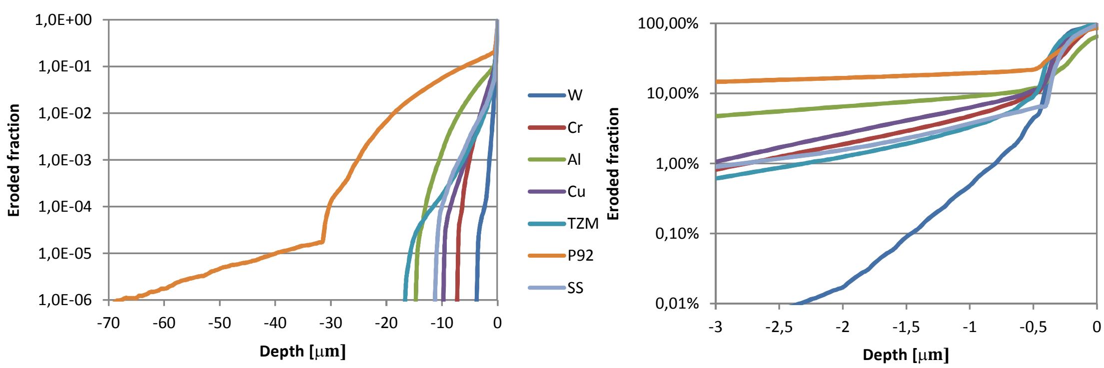

Figure 3 Depth profiles of the eroded areas for the materials used.

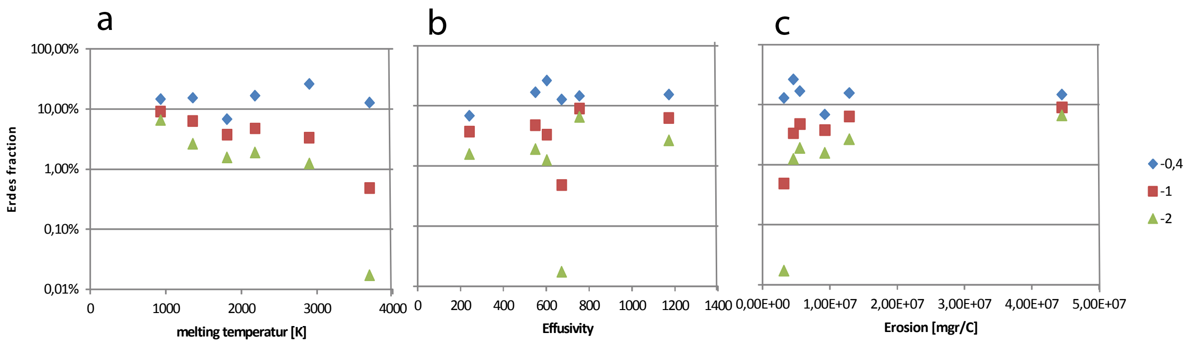

Figure 4: Comparison of the eroded areas for different depths. A: melting temperature, B: Thermal effusivity, C: Laboratory data [4]

The amount of eroded material as calculated from the eroded areas was put into comparison with different physical properties of the materials. The role of the melting is shown in Fig 4 a: whereas for a shallow depth (0.4 µm) the affected area is comparable for all material, bigger differences are shown for larger depths. The higher erosion for the Al and the smaller erosion for tungsten points to a non-linear behavior, a more complex model is needed. As expected a higher melting temperature reduces the erosion significantly. The thermal properties of materials are usually descripted by the thermal effusivity. As shown in Fig 4 b no simple correlation with the measured erosion is found. Comparing these data with older laboratory investigations yields a good correlation for depths smaller than 1 µm.

Summary and Conclusion:

Different materials were mounted in AUG at a region, which is prone for arcing. The erosion by arcs varies significantly depending on the occurrence of deposits. For magnetic materials the erosion is strongly enhanced, presumably due to the local change of the magnetic field direction. For this reason the erosion of P92 as reported in [1] is strongly enhanced. The erosion to a depth of 0.4 µm depends only weakly on the properties of the material. Deeper traces depend mostly on the melting temperature of the material. The data obtained are overall in line with old literature values. To investigate discrepancy of the thermal effusivity on the erosion, a more sophisticated two dimensional model is needed, which takes the short burning time of an arc on a single location into account.

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