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METHODS FOR ESTIMATING THE DAMAGE FACTOR OF MATERIALS UNDER THE INFLUENCE OF PLASMA

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¶ **Abstract:** *Experiments in the plasma focus device PF12 have been carried out by using deuterium for investigating the effects of a powerful deuterium ions stream and deuterium plasma on various steels and tungsten. The experiments were carried out at a deuterium pressure of about 10-15 Torr. The surfaces of the irradiated specimens are investigated by using electron microscopy. Also, the change of the roughness of the specimens surface was investigated. As cracks, holes and different other surface structures due to the plasma effect, and vaporization and deposition of metal on the surface appeared, surface roughness had essentially changed. The role of roughness as a possible quantitative factor indicating radiation damage on the surface is discussed.*

Key words: damage factor, roughness, uncertainty measurement.

1. INTRODUCTION

A number of different types of large fusion facilities – ITER (International Thermonuclear Experimental Reactor in France), LMJ (Laser Mégajoule in France), NIF (National Ignition Facility in USA) – are in progress. Many of the basic problems investigated and solved are common for both types of the main fusion energy facilities (magnetic and inertial confinement types) as well as for different alternative fusion facilities [[1]]. One of the main problems still insufficiently investigated is connected with material sciences and namely – how longstanding irradiation and heat loads generated in fusion devices affect the construction materials of fusion devices, which are directly exposed to plasma, X-radiation and neutron flow, as well as how it affects the materials used for construction and diagnostics (low-activation metal alloys, ceramics, optical materials). Therefore it is of utmost importance to carry out investigations by different types of devices including dense magnetized plasma devices, which can generate high power heat loads and irradiation to analyse structural defects in materials due to irradiation. Among the materials to be used for the construction of that kind of devices tungsten, CFC (chlorofluorocarbon), beryllium, tungsten alloys and low-activation stainless steels are considered [[2], [3]].

The following phenomenological formula for damage factor F has been found:

$$F \sim q\,t^{1/2}, \qquad (1)$$

where q is the power flux density and t is the duration of interaction of plasma and ions flow with materials. This relation is in good accordance with experiments if the damage factor is indicated by the number of defects per surface area [[4, 5]].

Nevertheless, alternative methods for the assessment of damage factors should be proposed, to estimate the damages caused by different plasma devices, and also, to estimate which kind of defects are the most important.

In this article two methods for estimating the damage factors will be proposed. Measurement of the micro-roughness of the damaged surface may give a good numerical characterization of the damage factor. The Pareto method for estimating of distribution of defects density in the irradiated area from SEM pictures is proposed as a development of the method in the article [4]. The Pareto method allows, besides the assessment of the damaged area, also indicates what kind of surface damages are the most important.

2. MATERIALS AND RADIATION CONDITIONS

The samples of low-activation ferritic stainless steels BS 183A and BS 92B as well as tungsten were in the form of 1 x 1 x 0.2 cm^3 plates. For the chemical composition of the steels see Table 1. The specimens were irradiated by high-temperature deuterium plasma (E_i~0.1-1 keV) accompanied with a fast ions stream (E_i~100 keV) generated by the dense plasma focus device PF-12 (Tallinn University). The initial pressure of the working gas was 12 Torr, the reference voltage of the capacitors was 20 kV, and distance of the specimens from the anode was 6.5 cm (see Fig.1). The pulse duration was about 100 ns and the number of neutrons per shot was estimated at 10^6-10^8. 1 pulse per 3 min was used. The power flux density of the deuterium plasma and fast ions streams used to irradiate the target materials was in the range of 10^6-10^7 W/cm^2.

Table 1. Chemical composition of the steels (in %).

Steel	183 A	92 B
C	0.172	0.15
Si	0.37	0.42
Mn	0.35	0.42
P	0.016	0.021
Cr	12.14	15.92
Mo	0.12	0.17
Ni	1.85	2.12
Co	0.036	0.04
Cu	0.93	0.13
Nb	0.006	0.006
Sn	0.003	0.006
V	0.09	0.07
W	0.006	0.02
In a minute amount: S, Al, Ca, N, O		

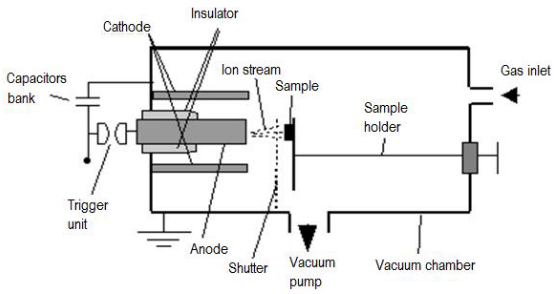


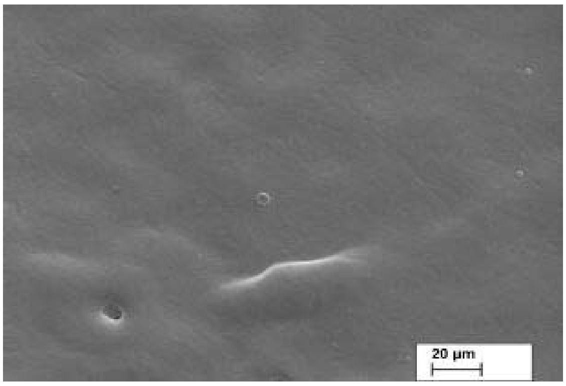
Figure 1. Experiment setup. The sample for plasma-ions irradiation is located on the holder at 6.5 cm from the anode.

3. ANALYSIS OF SURFACE MODIFICATIONS

The surfaces of the irradiated specimens were investigated by using scanning electron microscopy (SEM). The irradiated surface area was investigated by using the secondary electrons, which reveals the micro-geometry of the surfaces and allows to estimate the area and surface density of defects. Figure 2 presents SEM photos of the steels listed in Table 1, and tungsten irradiated by 2, 4 or 8 pulses. Analysis showed that in all samples various defects can be found: holes, splits, exfoliations, pores, bubbles, micro-cracks etc. A preliminary analysis by SEM photos reveals that in all cases a wavelike relief can be found, with a 60-80 µm wavelength for the steels. Another characteristic feature – tungsten irradiated at the same conditions has developed a mesh of micro-cracks. Also, the line of cracks seems to go by brittle lines with a width of about 20-30 nm. In steels there may be only a few cracks. It may be due to the lower melting temperature of steels – some cracks may have been covered by melted steel.

3.1. Measurements of micro-roughness

The micro-roughness of materials surfaces before and after irradiation by plasma was investigated by the Perthometer Concept MFW 250 (Mahr). The principle of scanning the surface-line by a diamond needle allowed to generate a profile of surface geometry [6]. Two samples of micro-roughness profiles scanned by tracing the irradiated area are given in Figure 3 The generated profiles were processed by a computer program, which gave different profile parameters: R_a, R_{max} (average profile height, maximum height of profile, accordingly), etc. As the surface of the irradiated samples is anisotropic, several nonparallel traces are needed for better profile parameters.



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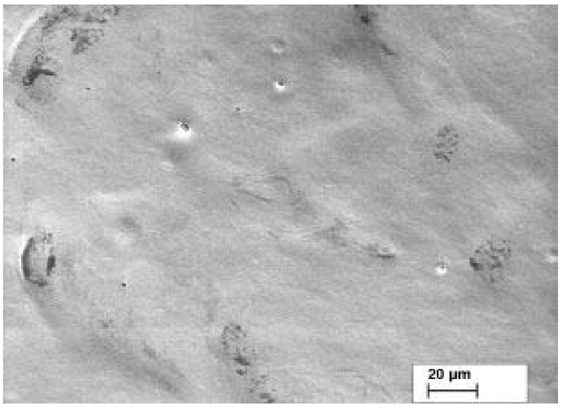

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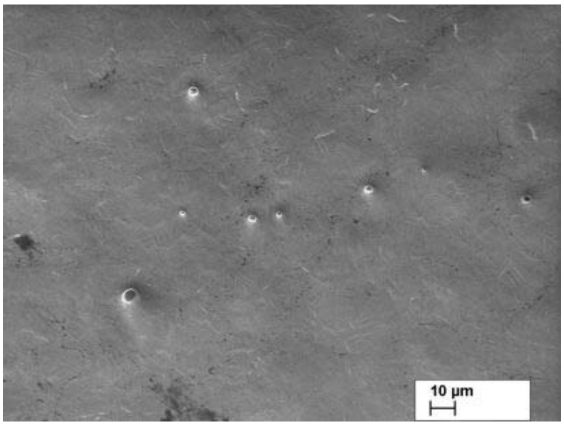

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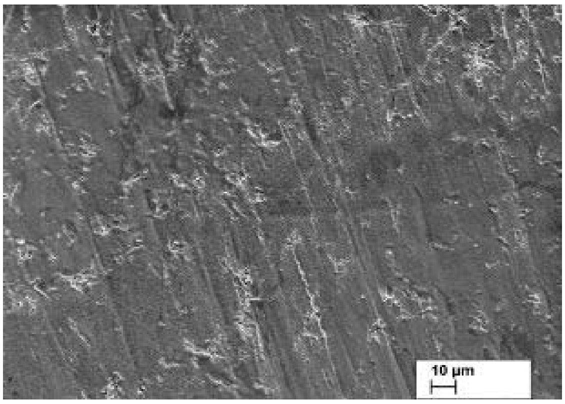

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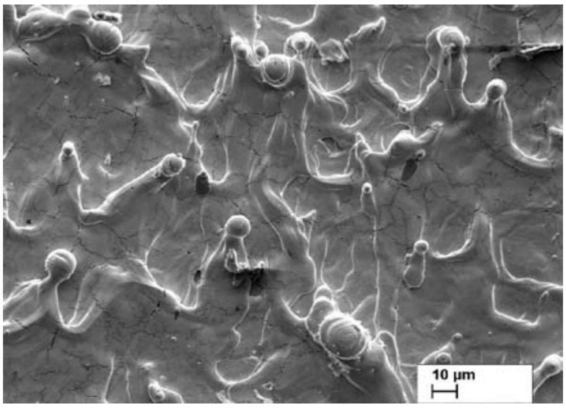

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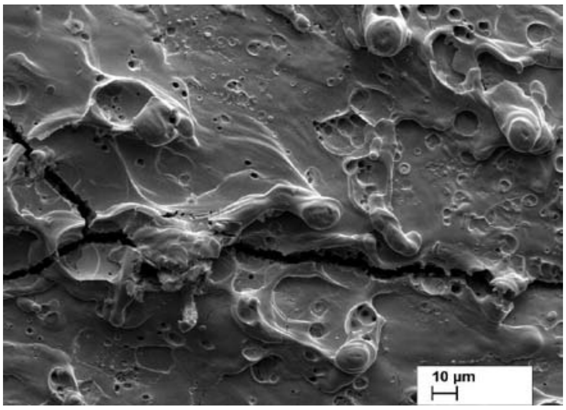


f

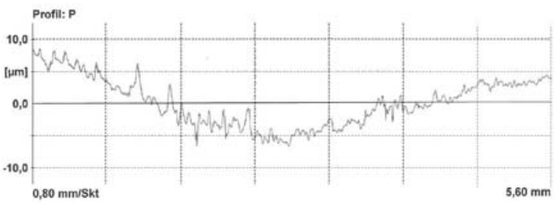
Fig. 2. Scanning electron microscopy of the surfaces of steels and tungsten: a – steel BS 183 A (2 shots); b – steel BS 183 A (8 shots); c – steel BS 92 B (2 shots); d – steel BS 92 B (8 shots); e – tungsten (2 shots); f – tungsten (4 shots)

Average heights R_a for different specimens are given in Table 2. As can be seen from Table 2, the average height of the micro-roughness profiles increases with the number of shots, generally. However, R_a seems not to increase linearly with the number of shots, and therefore also with power density, as it should be by Eq. (1).

Table 2. Microroughness of the materials

Material	R_a (µm)
Steel BS 183 A (2 shots)	0.392
Steel BS 183 A (8 shots)	0.596
Steel BS 92 B (2 shots)	0.184
Steel BS 92 B (8 shots)	0.705
Tungsten (2 shots)	0.91
Tungsten (4 shots)	1.26

In Figure 3 it can be seen that in the case of stainless steel (BS 183A) a layer with a thickness of about 12 µm has been eroded. In the case of tungsten the thickness of the eroded layer is about 1-2 µm. Therefore, it should be mentioned that the profile analysed by the perthomether is from a material surface which has been melted and repeated crystallized. Hence, the average height of the micro-roughness profile characterizes the damage factor only partly.



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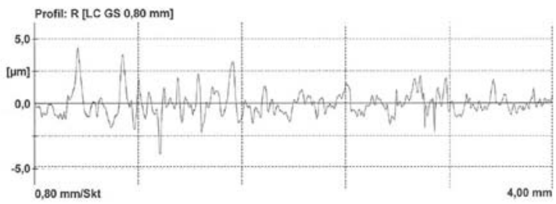

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Fig. 3. Surface profile of a stainless steel sample BS 183A (8 shots) scanned by perthomether. a) surface profile showing a hole in the surface; b) surface profile of the central part shown in a.

It is necessary to systematize the different damages of the irradiated materials for calculation the phenomenological formula for damage factor. The small damages can be consequence of the big one. Not all defects make an essentials contribution to surface damages, therefore the numerical definition of the damage factor quantity is calculated below.

3.2 The Pareto method

Another method to characterize defects density and therefore also the damage factor, is the Pareto method [7]. An illustration of the Pareto method for estimating the damage factor of an irradiated surface is given in Figures 4-6. On the X-axis there are the different kinds of damages and on the Y-axis there is area, which the defects take. The Pareto diagram is drawn by principle of relative area storage in percentage. The empirical dependence between the damage factor, power density of the plasma flux and time of influence (pulse duration) given by Eq. (1) does not reveal the exact value of the damage factor.

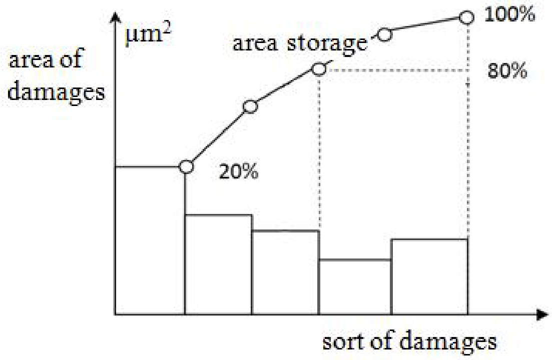

Fig. 4. Pareto diagram

The Pareto method allows to estimate the damage factor defined by the area of defects per unit area measured on the irradiated surface. Besides, the Pareto method reveals the most important kind of defects. For this paper the damage factor for modified surfaces of stainless steel samples was estimated by the Pareto method. In Figures 5 and 6 a Pareto diagram for steel samples 183A is given. It can be seen that for 2 shots only 1 or 2 kinds of defects play major role, whereas for the sample irradiated 8 times, different kind of defects have played a greater role. In Table 3 the damage factors for stainless steel samples are given. It can be concluded that the damage factor defined as area of damages per unit area is in good accordance with the empirical formula (1).

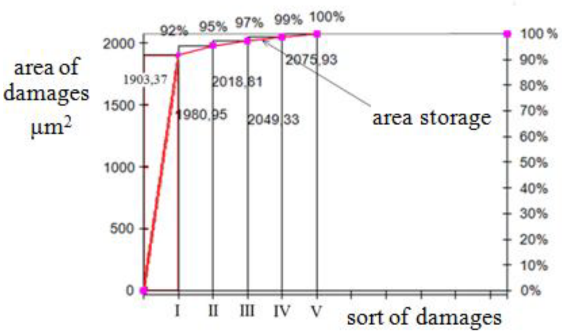

Fig. 5. Pareto diagrams for steel 183 A (2 shots): I – excrescence; II – craters; III – bubbles; IV – pores; V – drops.

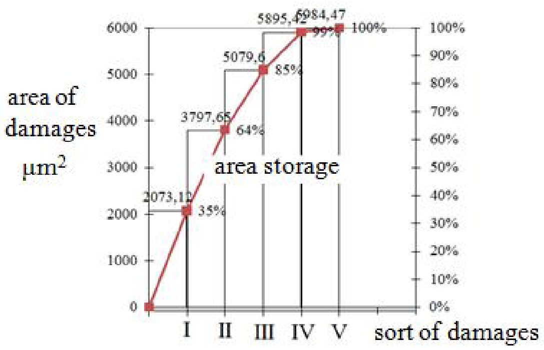

Fig. 6. Pareto diagram for steel 183 A (8 shots): I-IV – the different forms of excrescences; V – craters

Table 3. Damage factor of materials.

Material	Damage factor F
Steel BS 92B (2 shots)	0.3503
Steel BS 92B (8 shots)	1.232
Steel BS 183A (2 shots)	0.0467
Steel BS 183A (8 shots)	0.125

4. CONCLUSION

Researches have been carried out on stainless steels and tungsten with the different radiation conditions. The results indicate that:

- The damage factor is in correlation with the number of plasma flux shots and with the power flux density.
- The average height of the micro-roughness profile and the damage factor are in positive correlation.
- The Pareto method for the damage factor definition reveals the most important kinds of defects.

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