Investigation of Influence of Pulsed Deuterium Plasma on Surface of Chromium-manganese Steel with Use of Multifractal Parameterization

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ABSTRACT

This paper gives results on the interaction of a chromium-manganese austenitic stainless steel and a pulsed high current deuterium beam. Features of damages, phase-structural transformations and chemical content changes were investigated. The interrelationship between the characteristics of the topographical surface structure and the number of pulses is discussed on the basis of multifractal parameterization methods. This method provides additional information about the topographical surface structure and is very promising for approximate near-surface layer damageability analysis.

Keywords: Pulsed deuterium plasma; Multifractal parameterization; Chromium-manganese; **PACS classification codes:** 81.65.Mq

1. INTRODUCTION

The chromium-manganese austenitic steels 25Cr12Mn20W have a great potential to be applied in structural components of thermonuclear fusion devices /1-8/. The choice in favor of this material has been determined by the fact that austenitic chromo-manganese steels are materials of substantial stability and resistance to high radiative or thermal effects. In addition, the materials are corrosion stable and have high mechanical and high technological characteristics. Moreover, it is important to stress that these materials meet the demands necessary to fulfill their use in pulsed high current devices. Thus, it is possible to consider these materials as perspective ones for utilization in high-energy load units of modern installations to be exposed to any pulse powerful impact of a different nature.

Topography of the near surface layers, for many reasons, determines chemical, physical and mechanical properties /9-13/. Conventionally, metal surface structure is studied in terms of quantitative parameters characterizing the single structural elements or use of statistical characteristics such as roughness. However, properties of a system as a whole essentially cannot be determined only from the description of elements of this system /11-15/. Employing a concept of multifractals based on the use of a general concept of measure, one can ascribe to a structure under investigation the quantitative parameters characterizing the structure as a whole, in addition to the conventional methods of description /11-17/.

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2. EXPERIMENTAL PROCEDURE

The steel 25Cr12Mn20W was smelted into ingots and rolled up into plates with a 15 mm width, a 15 mm length and a 1 mm thickness. The chemical content of the steel is given in **Table 1**.

Table 1

Chemical content of steel

Steel				
	C	Cr	Mn	Si
25Cr12Mn20W	0.25	11.57	20.75	0.02
Steel	Elements, mass%			
	W	Ni	M	Ta
25Cr12Mn20W	2.01	-	-	-
Steel	Elements, mass%			
	V	P	S	
25Cr12Mn20W	0.1	0.04	0.008	

Samples were then irradiated using the Dense Plasma Focus device of Filippov-type electrode geometry with capacitor energy storage up to 60 kJ /1, 7, 18/, initial deuterium pressure about 40 Pa. The parameters of irradiation are shown in **Table 2**.

Table 2

Lattice parameter *a* of 25Cr12Mn20W steel specimens, initial and irradiated

Number of pulses	0	1	2
Lattice parameter ***a***, nm	36.047	36.120	36.134
Number of pulses	4	8	11
Lattice parameter ***a***, A	36.138	36.153	36.153

This Table shows that the 25Cr12Mn20W steel specimens were exposed to sequences of pulses. All specimens under irradiation were situated at a cathode of the Dense Plasma Focus device. Samples were irradiated by consecutive pulses of deuterium plasma with pulse duration 10^{-8} s, power flux density $10^{10}...10^{12}$ W/m^2, initial deuterium pressure about 40 Pa and the beam diameter 0.01 m. For the investigation of topography, we used the sliding bunch of x-ray beam method which was applied in a cylindrical chamber. An X-ray dot map was made using Co K_α radiation.

The specimens were irradiated at 4^0 and 2^0 angles of incidence of radiation on the surface of the sample. The depth of the analyzed layer was about 3 and 2 μm. Surface topographies were investigated by means of optical microscopy (**Fig. 1**) and imaged using a digitized camera "Malvica" MVC-FD7 (SONY). The optical axis was perpendicular to the sample surface. Digital image processing with increase in contrast gave discrete binary images. The image size was 480x480 pixels and it has a resolution of 72 pixels per inch (**Fig.2**). Here the white color corresponded to the most prominent features above the mean surface level.

With technique of multifractal parameterization /13-17, 19, 20/ of structures it is possible to describe the topography. The discrete approximations of structures at first were carried out by the assignment to the white elementary units (square boxes of the digitized image) symbol "1", and the black elementary units – "0". Subsequently, the matrices were partitioned into larger boxes, consisting of $l_k x l_k$ elementary units. For each rougher partition the characteristic measure was calculated with the distribution of the units P_i ($P_i=M_i/\Sigma M_i$, where M_i- a sum of units in i^{th} large box, ΣM_i-is the overall sum of units over the whole rougher partition, i=1, 2, 3..., N). Furthermore, conventional multifractal characteristics – D_q- spectra of dimension Renyi /21/ and /22/ with direct calculation of f (α) - spectra /23/ were determined. In comparison with earlier works /10-17/, the check of spectra is made for correctness for all subranges of scales by the criterion $f(q_1) \leq f(q_2)$ and $\alpha(q_1) \leq \alpha(q_2)$ for $0 \leq q_2 \leq q_1$. The multifractal characteristics were calculated as the averages on all correct spectra.

The technique allows quantitative estimation of relative degree of uniformity (f_{200}) and order ($\Delta_{200} = D_1 - D_{200}$) of structures. The greater f_{200}, the more uniform is the structure. The greater Δ_{200}, the more ordered is the structure /10-17/. Five (5) – six (6) images were processed for each surface. For these multifractal characteristics, central tendency and 95% confidence interval were calculated.

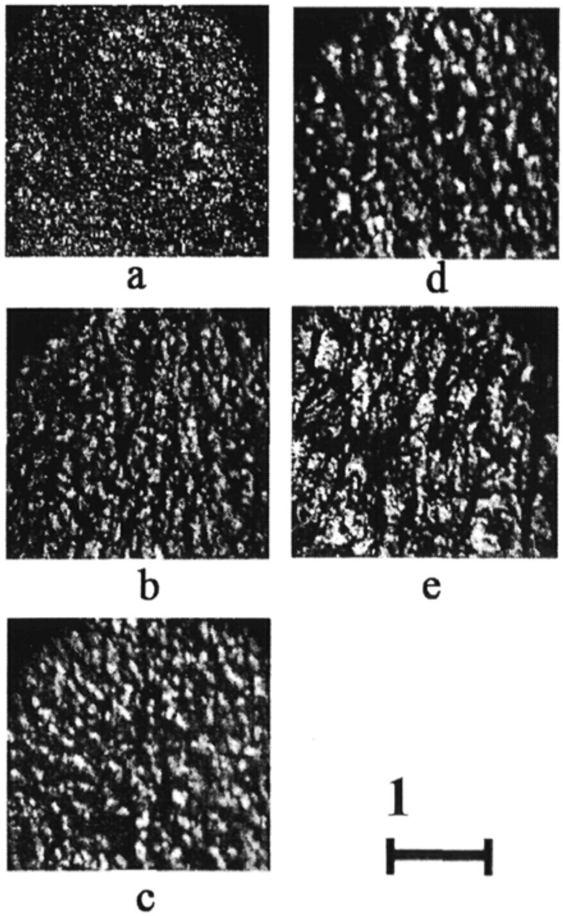

Fig. 1: Photographs of topographic surface structure of 25Cr12Mn20W steel specimens after different numbers of plasma pulses: a-1 pulse; b-4 pulses; c-8 pulses; d-11 pulses; e-120 pulses

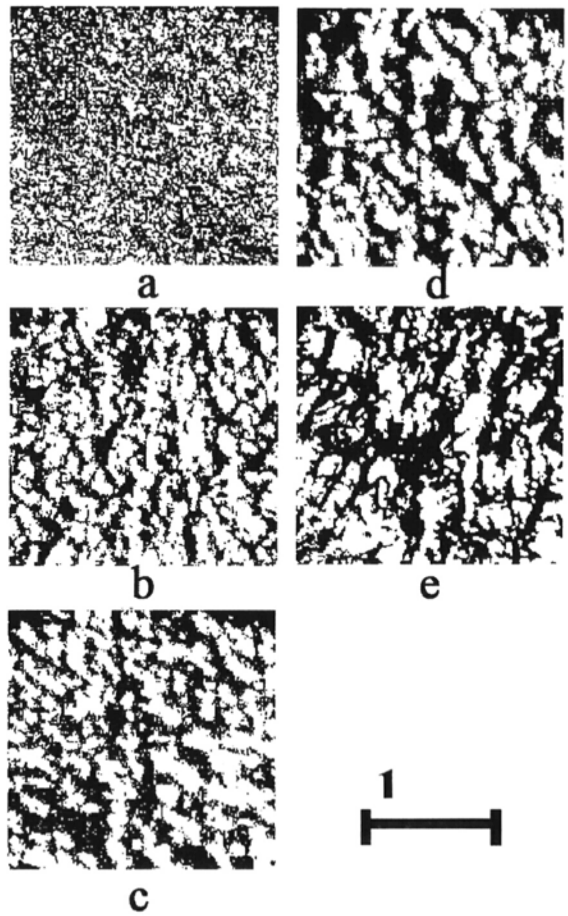

Fig. 2: White-black images of photographs of topographic surface structure of 25Cr12Mn20W steel specimens after different numbers of plasma pulses: a-1 pulse; b-4 pulses; c-8 pulses; d-11 pulses; e-120 pulses

3. RESULTS AND DISCUSSION

X-ray structural investigation showed that a nonirradiated sample has a single-phase austenitic structure and its texture is connected to the cold rolling of steel. After the influence of 8 pulses of deuterium plasma, the single-phase structure still remains on the surface. However, the γ- phase has some texture change (110); the structure becoming fine-grained with a low degree of distortion of the crystal lattice as the result of burn off and subsequent fast crystallization.

Chemical content measurement results showed that the contents of components in the 25Cr12Mn20W steel after8 pulses were not changed (**Table 3**). It should be taken into consideration that the crystal lattice parameter **a** increases in the irradiated specimens. Concerning an increase of the lattice parameter **a** with a number of pulses N (**Table 2**) the value of the increment was commensurable with the error of measurements. Nevertheless, one can believe that the lattice parameter increase under the plasma irradiation was connected with interstitial atoms in the γ-solution. The formation of an interstitial alloy usually resulted in an increase in volume of the elementary cell /24/.

Table 3

Chemical content of 25Cr12Mn20W steel after 8 pulses

	Chemical content, mass-%		
Element	Point #1	Point #2	Point #3
Fe	64.91	64.03	64.26
Cr	13.03	13.39	13.43
Mn	20.80	21.23	20.69
W	0.95	1.05	1.28
Si	0.32	0.30	0.33

Table 4

Multifractal characteristics of 25Cr12Mn20W after irradiation

	Multifractal characteristics		
The number of the pulses	D_{200}	Δ_{200}	f_{200}
1	1,86±0,02	0,11±0,02	0,28±0,09
4	1,82±0,02	0,15±0,01	0,41±0,17
8	1,76±0,02	0,20±0,02	0,26±0,15
11	1,74±0,01	0,20±0,01	0,35±0,05
120	1,66±0,02	0,25±0,02	0,39±0,13

Taking into account that a range of 100 keV deuterium ions in iron is less than 1 μm and the penetration of X-ray radiation is about 10 μm, the possibility of a direct implantation of ions into the lattice for the depth analyzed should be excluded. We assume that the appearance of interstitial atoms in the γ-austenite lattice results from a shock wave influence of the gas ions delivered to a surface liquid layer under the plasma irradiation. The shock wave action combined with a mass-transfer process resulted in abnormally deep penetration of the interstitial atoms into the alloy volume and in an increase of the γ-lattice parameter. Moreover, the shock wave action could result in a displacement of metal alloy atoms into an interstitial position and thus could influence the lattice parameter a increase.

Thus, considering the high cooling rate and the possible penetration of deuterium into steel from the atmosphere of the working chamber under the pulse action of deuterium plasma, the final microstructure may have a number of mechanical properties distinct from the initial non-irradiated condition.

Figure 1 shows a general view of the surface topography after irradiation by plasma pulses **(a-f)**. **Figure 2** shows their discrete black-and-white images and **Table 4** gives the derived multifractal characteristics.

The size of the beam spot does not depend to any extent on the number of pulses. After irradiation, the topography has a wave-like relief and a lot of droplets. After one pulse, there were small drops, close to hemispherical. Appreciable disorder in sizes and orientation of their arrangement was absent in this case. Some drops merged to form larger irregular shaped drops. Furthermore, additional pulses resulted in the droplets spreading onto the ridges, directed from the centre of the irradiated zone to its periphery. The number of non merged microdrops was found to decrease with an increase in the pulse number. It should be noted that after 120 pulses the small drops are almost absent. The ridge size increased in both width and length with an increase in the pulse number. At the same time, the number of merged ridges increased resulting in inflow formation, which resembled half moon or ellipses exposed to 120 pulses elongated and bent in the direction from center to periphery of the influence of plasma density on the spot ignition. It was established that a nanoparticle dispersed structure was formed in remolten surface layers which resulted in an increase in microhardness under influence of high-temperature dense deuterium plasma pulses. The results obtained show that the microhardness of near-surface layers (points #3, #4) differs from the non-irradiated material (points #1, #2, #5) (**Table 5**). The self-organization of the topography can be connected with the synergistic influence of the temperature field (gradient of temperature directed from the "cold" to "hot" layer) and the shock wave on melt. The shock wave was formed due to the injection of a cumulative air-plasma jet at the current sheath collapse and through the abnormal absorption of a relativistic electron bunch /7, 8, 18/ in the anode material. As a result, the fused material obtained becomes topographically oriented and this remained after crystallization. The increase in the number of consecutive pulses directed at a surface resulted in more complicated topography. The data of the multifractal parametrization are in good agreement with the qualitative methods of visual analysis. **Figure 3** shows the behavior of Renyi generalized dimension D_{200}, degree of uniformity f_{200} and hidden periodicity Δ_{200} after irradiation with various pulse numbers. The multifractal characteristics (D_{200}, Δ_{200}) and topography parameters linearly depend on the logarithm of number of pulses. The correlation coefficients exceed 0.975. Since the characteristics D_q (Renyi entropies) carry information on the thermodynamic conditions for structure formation /12-14, 17, 19-21/, therefore there is the precise interrelationship between the number of pulses and the quantity D_q (q=200). Larger values of D_q (at q>1) correspond to larger values of entropy /20/. The enlargement of Δ_{200}, along with increasing number of pulses shows that the structure becomes more uniform. According to information-theoretic interpretation of multifractal formalism /11/, the parameter Δ_{200} being the estimation of $\Delta_{\infty}=D_1-D_{\infty}$ corresponds to extreme value of multifractal information and reflects the degree of broken symmetry /20, 23/. In fact, increasing Δ_{200} parameter suggests that the system is filled with information (negentropy) /20, 25/. The degree of broken symmetry grows with an increasing number of pulses. That is why the self-organization of the surface topography becomes complicated with an increasing number of pulses. The parameter of uniformity f_{200} of the surface topography varies insignificantly. Probable instability of plasma parameters /1-8 / enables a wide scatter of values of f_{200} The results suggest the complicated nature of the mechanisms of surface shaping and evolution of topographical structure. Probably at some stage during the pulsed irradiation, the dissipation of the absorbed energy results in soliton formation on the liquid-phase surface subsequently deformed by shock waves. This question should be considered separately.

The chemical content of the alloy before and after the irradiation (without any changes) shows that physical and chemical processes (evaporation, melting, crystallization and so forth) under a nanosecond pulse plasma action do not result in any noticeable redistribution of the alloy components.

Table 5

Microhardness of near-surface layers (points 3, 4) and non-irradiated material (points 1, 2, 5), GPa

Number of pulses	Point #1	Point #2	Point #3	Point #4	Point #5
1	0.69	0.65	0.67	0.63	0.61
4	0.69	0.66	0.81	0.83	0.63
8	0.75	0.77	0.88	0.95	0.66
11	0.69	0.74	0.99	1.13	0.74

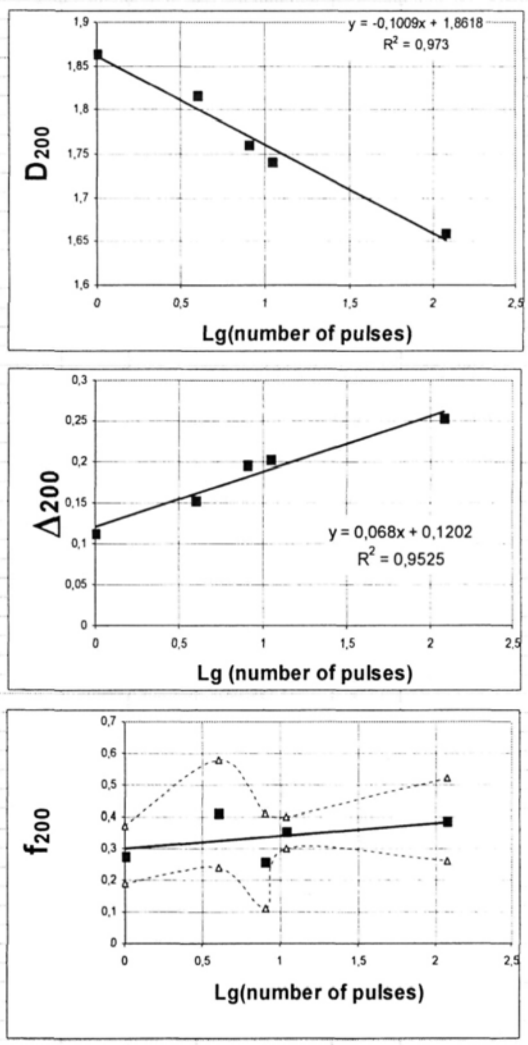

Fig. 3: The character of changes of a generalized dimensions Renyi D_{200}, hidden periodicity Δ_{200} and a degree of uniformity f_{200}.

4. CONCLUSION

The influence of the deuterium plasma pulses on the materials studied has resulted in formation of the surface relief of large ridges and influxes with the radial orientation.

With multifractal parameterization methods it has been shown that the characteristics of the topographical surface texture have logarithmic dependence on number of pulses. Increasing number of pulses favors the formation of more complicated and ordered relieves. After irradiation of the near-surface (up to 3 mkm), the phase structure did not change. However, it gained a fine-grained character. Of particular interest is the decreasing ability of the material to dissipate energy under pulse plasma action.

It has been shown that methodology of multifractal parameterization of structures is useful for approximate near-surface layer damageability analysis.

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