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ORIGINAL PAPER

Influence of dense deuterium plasma pulses on materials in Plasma Focus device

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Abstract Experiments on the influence of high-temperature plasma nanosecond pulse radiation, as generated in plasma focus device, on the W-Cu pseudoalloy, V-35at%Ti alloy, austenitic chromium-manganese 10Cr12Mn20W and 25Cr12Mn20W steels have been carried out. Features of damages, phase-structural transformations and chemical content changes in those materials under such irradiation were investigated.

Key words high-temperature plasma • material science • plasma focus

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Introduction

Formerly, in Ref. [5] damages and structure changes in materials, as developed for energy loaded components of a thermonuclear fusion reactor under nanosecond pulses of deuterium plasma (DP) with a power flux density of 10^4–10^7 MW/cm^2, have been investigated. For model materials, such as W-Cu pseudoalloy, austenitic chromium-manganese steel and V-Ti alloy, it was shown that the plasma focus device (PF) can be used successfully for simulation of interaction studies of TOKAMAK plasma and first wall materials. The simulation was especially advanced for extreme situation with plasma disruptions, runaway electrons etc. It was noted that the possibility of a combined treatment of materials with pulse ion and electron beams, X-rays, neutrons, high temperature plasma and shock waves, is an important feature of PF. Surface modification (improvement of a structure and properties of a material in a thin surface layer) under this irradiation may be useful for solving problems connected with development of a new technology of surface treatment [2–5].

In the present work the main results obtained in [5], as well as original investigations of the damage and structural and phase transformation in the austenitic chromium manganese steel 25Cr12Mn20W under pulses generated in the PF device, have been presented. Structural and phase stability of the investigated materials under the considered radiation and thermal conditions was compared.

Materials and experiments

Materials under investigation were as follows: a W-Cu pseudoalloy (porous tungsten preinfiltrated by copper), an

austenitic steel 25Cr12Mn20W and a V-35at%Ti alloy. The W-Cu pseudoalloy was prepared by means of a powder metallurgy technique: powdery W was sintered at a high temperature and infiltrated by liquid copper. The steel was melted and rolled up to a thickness of 1 mm. Specimens of the V-35at%Ti alloy were rolled up to a thickness of 1 mm, and annealed at a temperature of 1273K for 1 hour under vacuum conditions of a residual pressure $p = 10^{-4}$ Pa. Specimens for experiments were prepared as plates of 1.5×1.5×0.1 cm.

Irradiation of specimens was carried out using a PF device with Filippov geometry [5] of energy up to 60 kJ. Ambient gas was deuterium at a pressure of about 0.3 torr. Parameters of the irradiation are presented in Table 1. The Table shows that the 25Cr12Mn20W steel specimens were exposed to sequences of pulses (from 1 up to 120). Power flux density was varied in the range from 10^5 to 10^6 MW/cm^2, and pulse duration was approximately 10^{-8} s. All specimens under irradiation were situated at a cathode of the PF device. Microstructure of the irradiated specimens was investigated by means of an optical and scanning electron microscopy as well as X-ray diffractography. A diffractometer of DRON-UM type and a scanning microscope of JSM-6400 type were used. Residual stress σ in the primary and irradiated specimens was studied using the so-called $sin^2\varphi$ method. Calculations of σ were carried out using the standard values of elasticity E and Poisson ν. For the W-Cu pseudoalloy the displacement of the (310) X-ray diffraction peak was measured and values $E = 4.1\times10^5$ MPa and $\nu = 0.278$ were used.

Table 1. Parameters of the pulse deuterium plasma irradiation.

Materials	# specimens	Number of pulses	Power density q, MW/cm^2	Pulse duration, τ, s
W–Cu	1	1		
	2	3	10^5–10^6	10^{-8}
	3	8		
V–Ti	1	1		
	2	4	10^5–10^6	10^{-8}
	3	8		
Steel 10Cr12Mn20W	1	1		
	2	4	10^5–10^6	10^{-8}
	3	8		
	4	13		
Steel 25Cr12Mn20W	1	1		
	2	4		
	3	8		
	4	11	10^5–10^6	10^{-8}
	5	5		
	6	20		
	7	120		

Results and discussion

Analysis of irradiated specimens surfaces show that (under the DP pulse irradiation) surface layers of all the materials were melted, evaporated and sputtered. Features of surface damage and phase-structure changes were different for the considered materials.

Fig. 1 shows scanning electron microphotographs of the W-Cu pseudoalloy surface before and after the DP pulse irradiation. On the primary surface one can see traces of a mechanical treatment (Fig. 1a). After a single pulse irradiation, on the surface a lot of melted microdroplets have appeared (Fig. 1b). When the number of pulses was increased then multifold remelting of the surface layer has resulted in some smoothing out of the surface roughness (Fig. 1c). X-ray diffraction patterns of W before and after the DP pulse irradiation are presented in Fig. 2. One can see that after the plasma irradiation diffraction peaks were more diffuse and the (200) peak was reduced. These effects became more obvious when the number of pulses was increased. Considered behaviour results from a distortion of the crystal lattice and appearing in local non-uniformities under the irradiation. Noted microstructure changes may result from an increase in a nonequilibrium vacancy concentration under quenching of the melt as well as for interstitial impurities. An interesting result was detected for tungsten base of the W-Cu pseudoalloy: X-ray diffraction patterns show unknown peaks corresponding to interplanar spacing of 2.022 and 1.418 A. Additionally, peaks of tungsten became asymmetrical unlike of symmetrical peaks for the initial state and after a single and triple irradiation (Fig. 2).

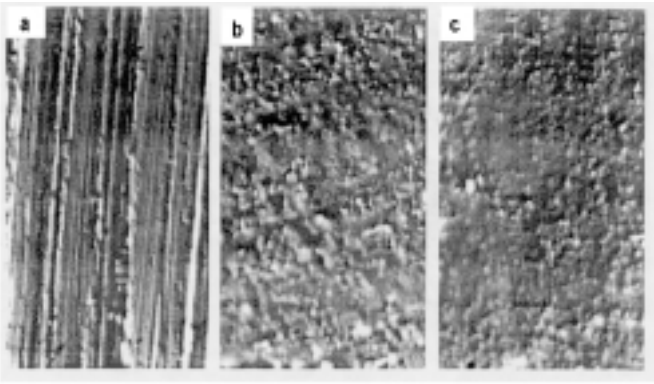

Fig. 1. Scanning electron microphotographs of the surface of W-Cu pseudoalloy in the initial state (a) and after the deuterium plasma irradiation: (b) – with 1 pulse; (c) – with 8 pulses.

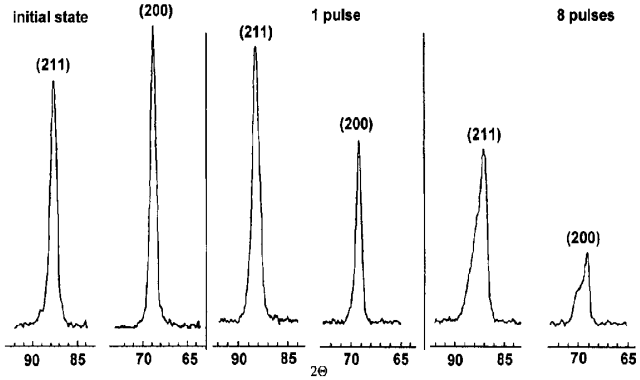

Fig. 2. X-ray diffraction patterns of tungsten in W-Cu pseudoalloy.

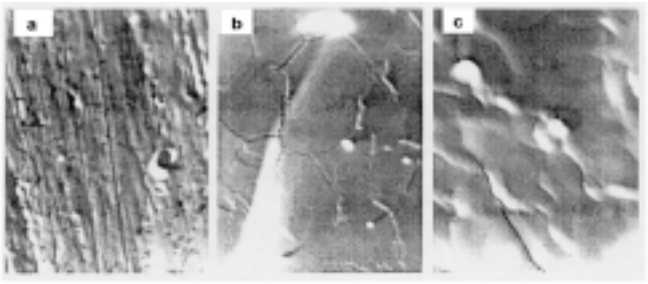

Fig. 3. Scanning electron microphotographs of the surface of V-35at%Ti alloy in the initial state (a) and after the deuterium plasma irradiation: (b) – with 4 pulses; (c) – with 8 pulses.

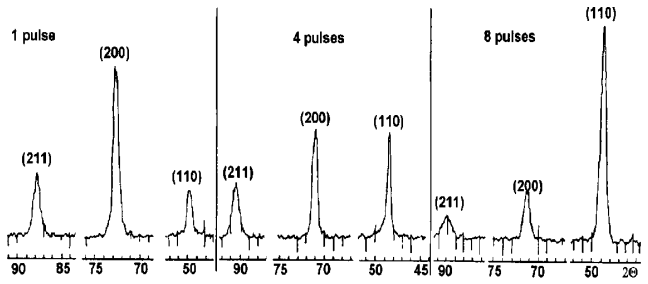

Fig. 4. X-ray diffraction patterns for the V-35at%Ti alloy after pulse deuterium plasma irradiation.

Other features of surface structure were observed after the irradiation of a V-Ti alloy (Fig. 3). In this case a surface relief consists of a number of merged droplets directed from the centre of the irradiated zone to its periphery. Beside that a lot of microcracks was formed on the surface. Fig. 4 shows X-ray diffraction patterns for single and multiple irradiated V-Ti specimens. The change of the crystallographic texture after the pulse DP irradiation was observed: rolling components of the texture (200) and (211) reduced. On the other hand, the component of the crystallization texture (110) increased (Fig. 4) when the number of pulses was increased. The fact results from a multifold recrystallization of the surface layer and the non-steady state heat influence on the more deep solid layers under each pulse irradiation.

Scanning electron microphotographs of the initial and pulse-irradiated 10Cr12Mn20W steel specimens are presented in Fig. 5. Features of a surface damage in this case was similar to the specimens V-35at%Ti, but ridges forming during the surface layer crystallization in steel specimens were longer than in the V-Ti specimens. Non-steady state heat influence was obviously the main reason of the phase-structure change after the DP irradiation of those steel specimens. In Fig. 6 one can see that the DP irradiation results in a significant change of relative volumes of austenite (γ) and ferrite (α) phases in the steel: (γ-phase content decreases and α-phase content increases). This effect is governed by the number of the DP pulses: under a single pulse irradiation the γ-phase content was ≈50–55 vol%; under the four-fold irradiation it decreased to ≈30–35 vol%; and under the eight-fold irradi-ation it decreased to ≈20–25 vol%. Thus, the DP irradiation of chromium-manganese steel results in the $\gamma \rightarrow \alpha$ phase transformation in a surface layer. Phase transformations of 25Cr12Mn20W steel in carried out experiments may be detected from X-ray diffractograms presented in Fig. 7. An increase in $(220)_\gamma$ X-ray peak and reduction of $(111)_\gamma$ X-ray peak were observed when the number of the pulses was increased. Moreover, in the irradiated specimens $(110)_\alpha$ and $(200)_\alpha$ X-ray peaks of α-phase were fixed, as well as in the 10Cr12Mn20W steel considered previously. The α-phase content increases with an increase in a number of pulses. A weak increase of crystal lattice parameter *a* of the γ-phase in irradiated 25Cr12Mn20W specimens, as compared with initial ones was found and this effect was enhanced with a number of pulses increase (see Table 2).

A chemical content of the irradiated material was studied in the 25Cr12Mn20W steel specimen after irradiation with 8 dense plasma pulses. Metallographic polishing section was made with an inclination of 10° to irradiated surface of the specimen. Three characteristic points were studied: #1 close

Number of pulses	0	1	2	4	8	11
Lattice parameter *a* , A	3.6047	3.6120	3.6134	3.6138	3.6153	3.6153

Table 2. Crystal lattice parameter a of 25Cr12Mn20W steel specimens (initial and irradiated).

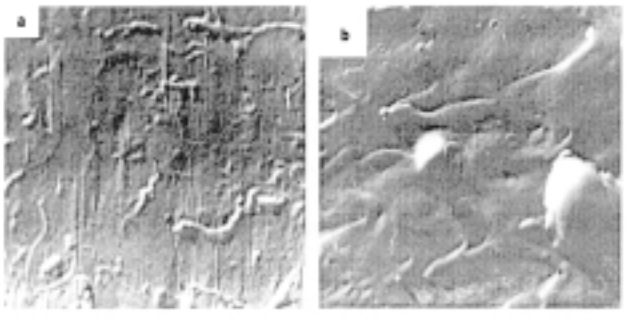

Fig. 5. Scanning electron microphotographs of the surface of steel 10Cr12Mn20W: (a) – in initial state, (b) – after 8 pulses of the deuterium plasma irradiation.

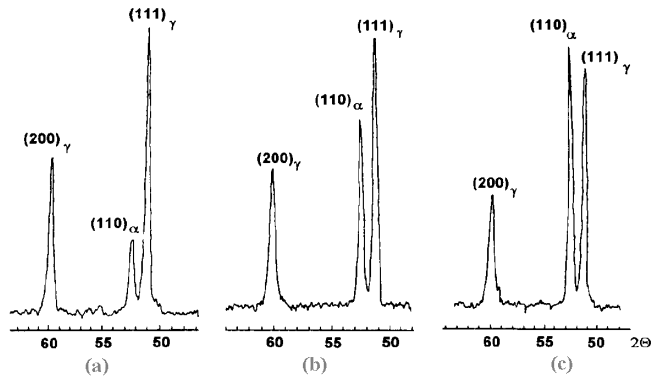

Fig. 6. X-ray diffraction patterns for the 10Cr12Mn20W steel after pulse deuterium plasma irradiation: (a) – 1 pulse, (b) – 4 pulses, (c) – 8 pulses.

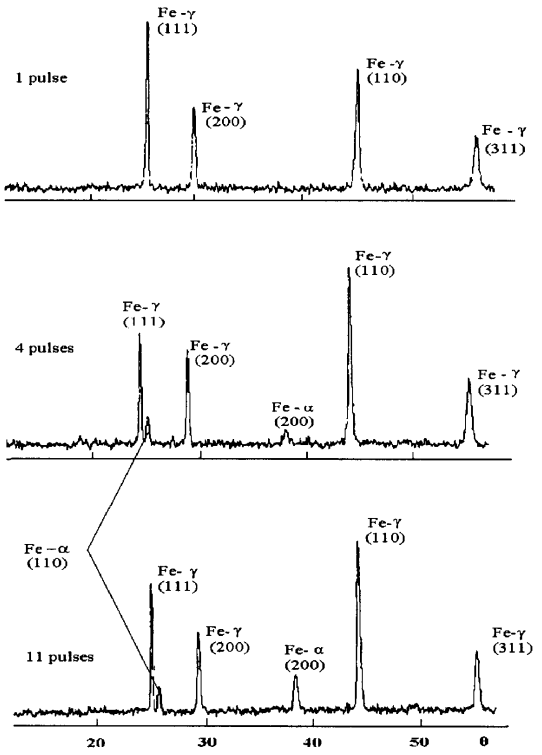

Fig. 7. X-ray diffraction patterns for the 25Cr12Mn20W steel after pulse deuterium plasma irradiation.

to the irradiated surface, #2 near the interface between the remelted zone and non-melted zone and #3 far from the irradiated surface. The point #3 was considered as a sample without influence of irradiation. Results of electron probe X-ray spectral measurements are presented in Table 3. One can see that the chemical contents in points #1, #2 and #3 are identical, taking into account a measurement error (< 3 mass%).

In paper [5] the above mentioned α-γ phase transformation was supposed to be connected with the impoverishment of manganese in the heat influenced surface layer due to its evaporation. However, chemical content measurement results show that the contents of components in the 25Cr12Mn20W steel after the pulse DP irradiation was not changed (see Table 3). So, the reasons of the α-γ phase transformation need special investigations. It should be taken into consideration that a crystal lattice parameter increases in the irradiated specimens of steel 25Cr12Mn20W with increasing pulse number. At present stage of investigation we can certainly affirm only the fact of lattice parameter increase in the

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

irradiated specimens, as compared with the initial ones. Concerning an increase of the lattice parameter with a number of pulses N (see Table 2) a value of the increment is commensurable with an error of measurements and the result needs additional verification. Nevertheless, one can believe that the lattice parameter increase under the plasma irradiation is connected with interstitial atoms in the γ-solution. The formation of an interstitial alloy usually results in an increase in volume of the elementary cell [7]. Taking into account that a range of 100 keV deuterium ions in iron is less than 1 μm the possibility of a direct implantation of ions into the γ-austenite 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 results in an anomaly deep penetration of the interstitial atoms into alloy volume [6], 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 it could influence the lattice parameter increase. Probably, the action of a shock wave stimulates the α-γ phase transformation in 25Cr12Mn20W and 10Cr12Mn20W steels, as considered above.

In general, investigation of a shock wave (generated by a pulse discharge in the plasma focus device) and its influence on the ions propagation into an irradiated material, as well as on the probability of phase transformation in solid state, is of evident interest. The chemical content of the alloy before and after the irradiation (without any changes) shows that physical and chemical processes under a nanosecond pulse plasma action do not result in a noticeable redistribution of the alloy components.

Conclusion

1. The experiments on the influence of high-power pulse plasma streams of a nanosecond range (as generated in the plasma focus device) on the W-Cu pseudoalloy, V-35at%Ti alloy and austenitic chromium-manganese steels (25Cr12Mn20W and 10Cr12Mn20W), have been carried out. Features of the damage and phase-structural transformations in these materials were investigated.
2. Under the considered conditions all the investigated materials were undergone surface melting and following quenching with the formation of a crystallization texture directed along the gradient of temperature.
3. A surface relief of the irradiated W-Cu pseudoalloy was shown to consist of remelted microdroplets, while the surface relief of other investigated materials consisted of large ridges and influxes with the radial orientation.
4. Influence of the DP pulses on the materials studied has resulted in (i) the W crystal lattice distortion and the appearance of unknown peaks on tungsten X-ray diffraction patterns in the W-Cu pseudoalloy; (ii) surface microcracks and changes of the crystallography texture in the V-Ti alloy; (iii) the γ→α phase transformation in

austenitic steels. These effects became more obvious when the number of pulses was increased.

5. In the irradiated specimens of the 25Cr12Mn20W chromium-manganese steel the crystal lattice parameter was found to increase as compared with the initial state. This fact may be connected with the interstitial impurities (deuterium, hydrogen, carbon), that penetrated into the γ-austenite under the irradiation and shock wave action.
6. On an example of 25Cr12Mn20W steel a comparison of the chemical content of the initial alloy and that after eight-fold pulse irradiation was made. It have been noticed that under pulse power plasma flows of nanosecond range (generated in the plasma focus device) there is no redistribution of elements in a surface layer.

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