Influence of pulse high heat fluxes upon the material of low activation austenitic steel tube in the dense plasma focus device

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ABSTRACT

The characteristics of the material damage, structural changes and distribution of the components in the surface layer of the low activated austenitic steel 25Cr12Mn20W under pulsed influence of deuterium ions and plasma beams have been determined for the hexahedral tube, which was placed in the cathode part of the Dense Plasma Focus device PF-1000 along the chamber axis. Irradiation of specimens was performed by microsecond high heat plasma and ions pulses with power density in the range of $q = 10^6 – 10^9$ W/cm^2 .

It was found that conditions of interaction of the pulsed energy beams with material were different both for internal and external surfaces of the tube and for different parts of each facet. This fact resulted in different effects observed. As a rule in re-melted surface layers in addition to austenitic γ - phase the martensite and α - phase were observed. This phase transformation leads to an increase of micro-hardness and strengthening of the layers. The action of extreme energy fluxes resulted in redistribution of the components of the steel in the surface layer and penetration of the copper into the melted layer. These effects were observed for both internal and external surfaces of the tube. The highest concentration of copper and carbon was seen in the surface of the steel. It was found that content of manganese was lower and content of iron was higher in the external surface layer compared to the internal one.

At the so-called “cold” part of the external surface of the tube the specific configuration of arrangement of the structural defects (bubbles and rings) was found.

Introduction

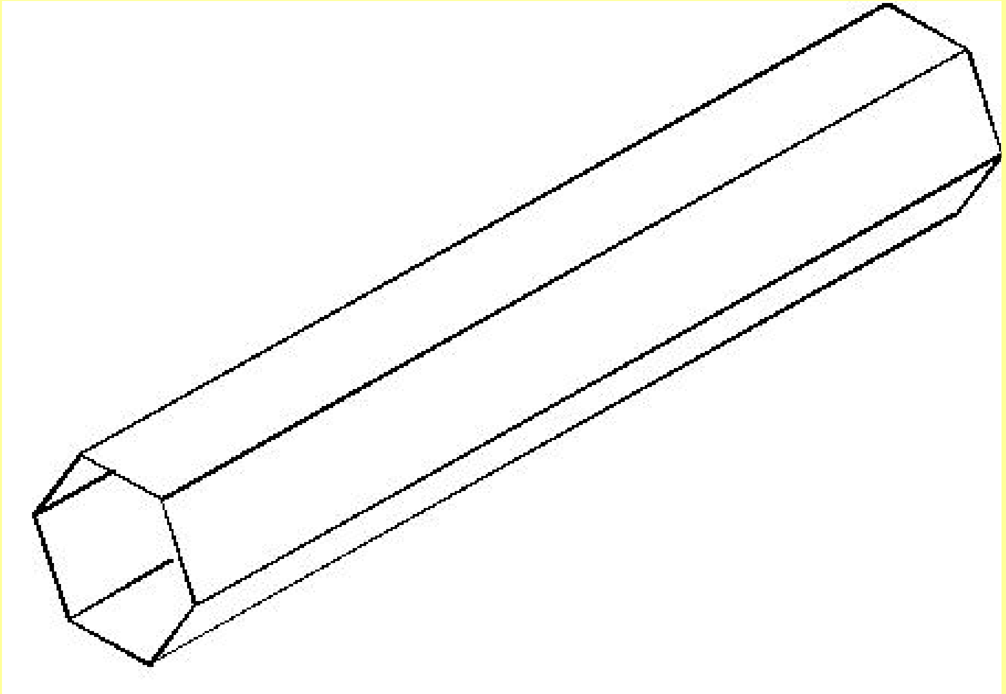
Papers [1,2] reported the experiments on the pulsed high temperature deuterium plasma *(DP)* irradiation of aluminum alloy tube placed along the axis of Plasma Focus *(PF)* device (PF-1000) chamber. Special metal screen was placed on the side of the tube which faced the anode. It protected the inner surface of the tube against all kinds of irradiation and the external surface against a direct beam of high-energy deuterium ions (*E* ≥ 100 keV) and X-ray.

Power density on the tube surface was 2 – 3 orders of magnitude lower compared to the corresponding value on the front surface of the screen. The pulse duration was increased up to a few microseconds. Irradiation conditions in this case were close to plasma disruption mode in the ITER.

The present project continues the investigations that were begun in [1,2]. The main object of the present work is to study the features of material damage, structural changes and distribution of the components in the surface layer of the low activation austenitic steel tube under the pulsed influence of deuterium ions and plasma beams in the *PF* device.

The steel tube was made in the form of a regular hexahedral prism.

Scheme of 25Cr12Mn20W steel hexahedral tube

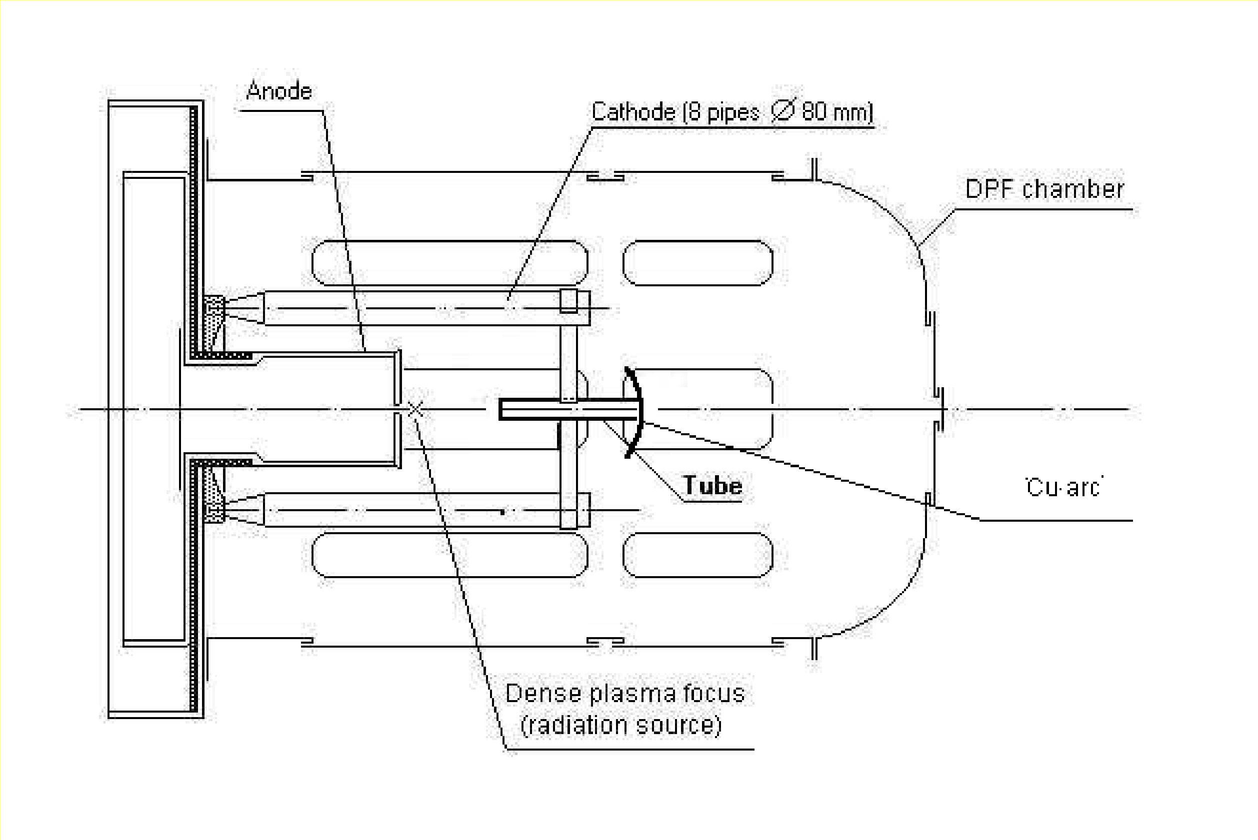


Formerly similar hexahedral tubes made of different stainless steels were investigated as covers of heat-generating elements for thermonuclear fission reactors [3]. Tube #14 (25Cr12Mn20W) was selected for our experiments. The length of the tube *(L)* was 30 cm, the width of each facet *(a)* was 2.2 cm, the diameter of external circle was 4.4 cm and the thickness of the wall *(h)* was 0.1 cm. The tube was manufactured by rolling.

Chemical composition of the steel tube **Table**

Steel	Elements, mass %								
	C	Cr	Mn	Si	W	V	Sc	P	S
25Cr12Mn20W	0.28	12.9	19.3	0.13	2.0	0.15	0.1	0.04	0.008

Scheme of PF-1000 device



The tube was placed along the axis of PF-1000 device. The tube was strongly fixed on two cathode cylindrical tubes by means of special copper holders. The distance between the anode and the nearest tube cut was *L_1* = 11cm. On the opposite cut of the tube a copper arc was fixed (see Figure). Its dimensions were: arc radius *R* = 25cm, arc length *L(Cu)* =30 cm, flat width *a(Cu)* = 1.5 cm and thickness *h(Cu)* = 0.12 cm. The arc closed the back cut of the tube and prevented the ion and plasma streams going freely out of the tube. The parts of the copper arc, which were not within the tube, got irradiated by scattered ion and plasma beams.

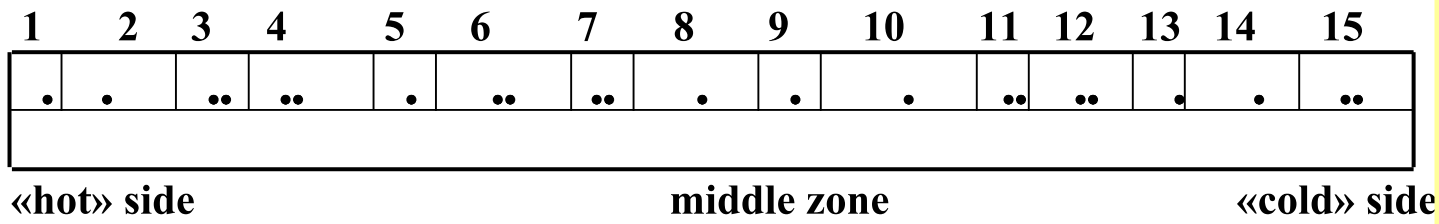
Irradiation conditions

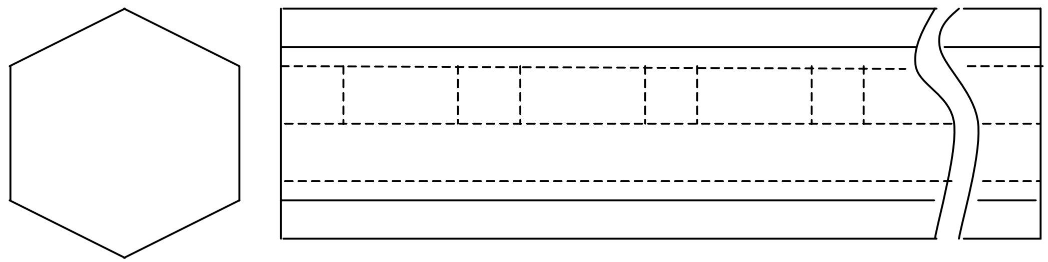
- The energy store of the device PF-1000 was ~ 600 kJ.
- Pure deuterium at the initial pressure of 470 Pa was used as working gas.
- Duration t of *DP* pulse moving over the plane of the front cut of the tube was 1 mcs.
- Power density of the plasma beam *q* was ~ 10^6 - 10^9 W/cm^2
- The total number of pulses in our experiments *N* = 4.
- Neutron output in separate "shots" *n* = (10^9 - 10^{11}).

Measurements and analysis

- Photography (by digital camera SONY DSC S85 and microscope NEOPHOT)
- Cutting of irradiated tube
- Micro-hardness measurements
- Chemical content analysis (in atomic emission spectrometer SA-2000 by means of analysing the layers removed from the surface to the bulk.)
- Local X-ray spectral analysis (using Cam Scan 4DV facility)
- X-ray diffraction analysis

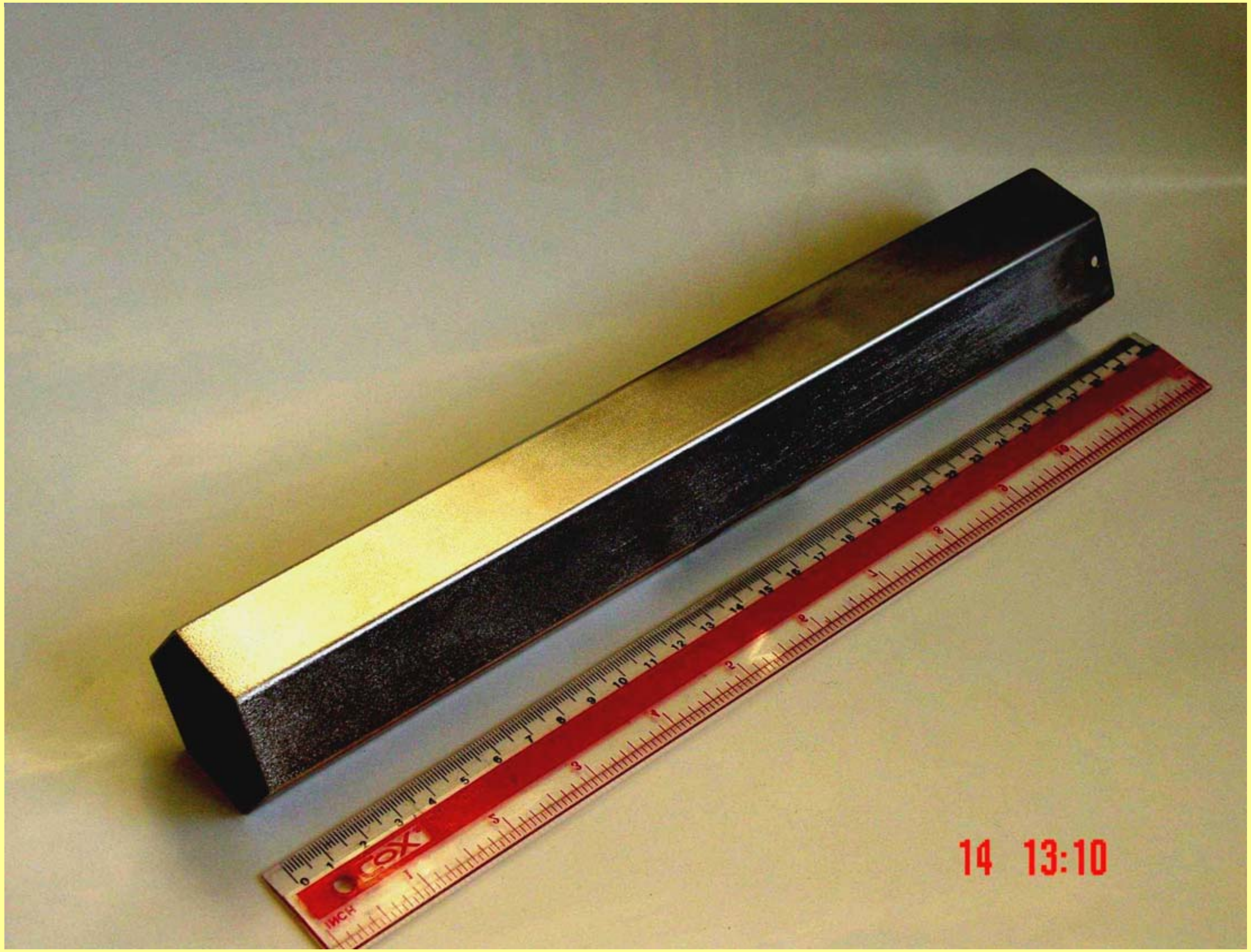
Scheme of cutting and marking the specimens of the irradiated steel tube





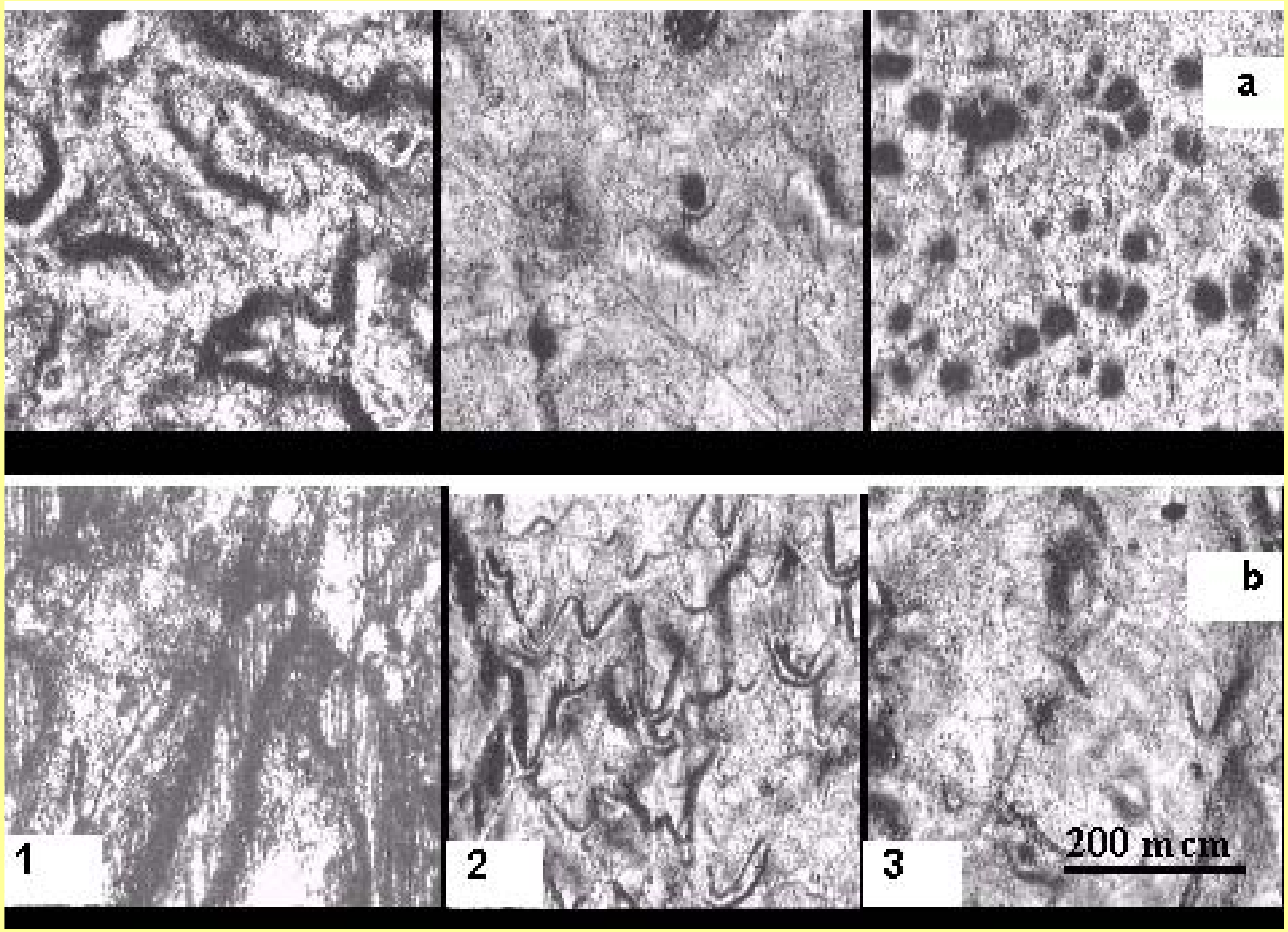
For different types of analyses two facets (30 x 2 cm²) of the tube were cut out. Then each of the facets was cut into two equal flats (30 x 1 cm²). One of the flats was subjected to a subsequent analyses and was cut into 15 specimens 1x 1 and 2 x 1 cm² as is shown in the Figure.

Hexahedral steel 25Cr12Mn20W tube after 4-fold pulsed deuterium ion and plasma irradiations in PF-1000 device



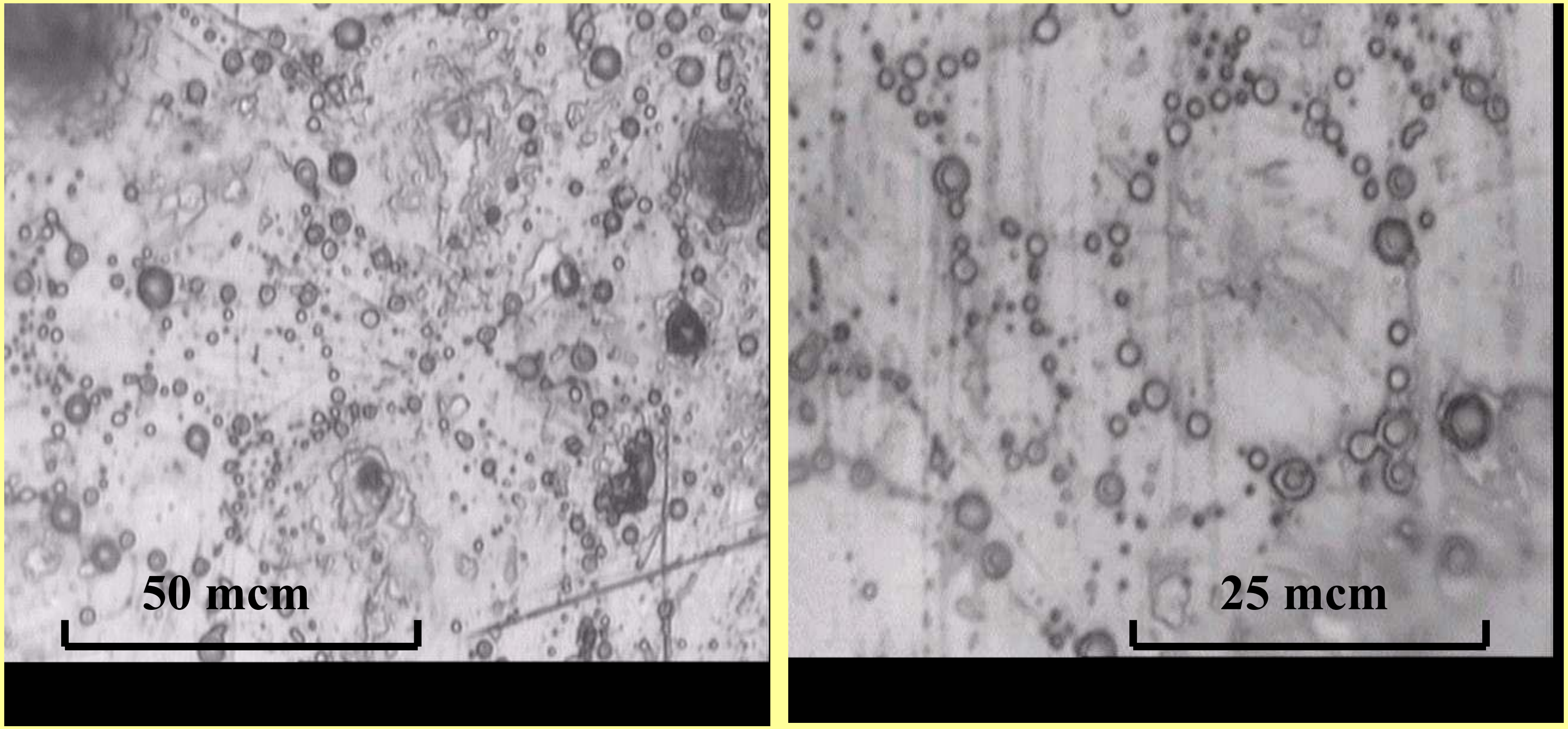
Visual analysis showed the melting of both the inside and the outside surfaces of the tube.

The parts of the external (a) and internal (b) surfaces of the tube: 1 – at the "hot" zone (specimen #2), 2 - at the middle part (sp. #8) and 3 – at the "cold" zone (sp. #14)



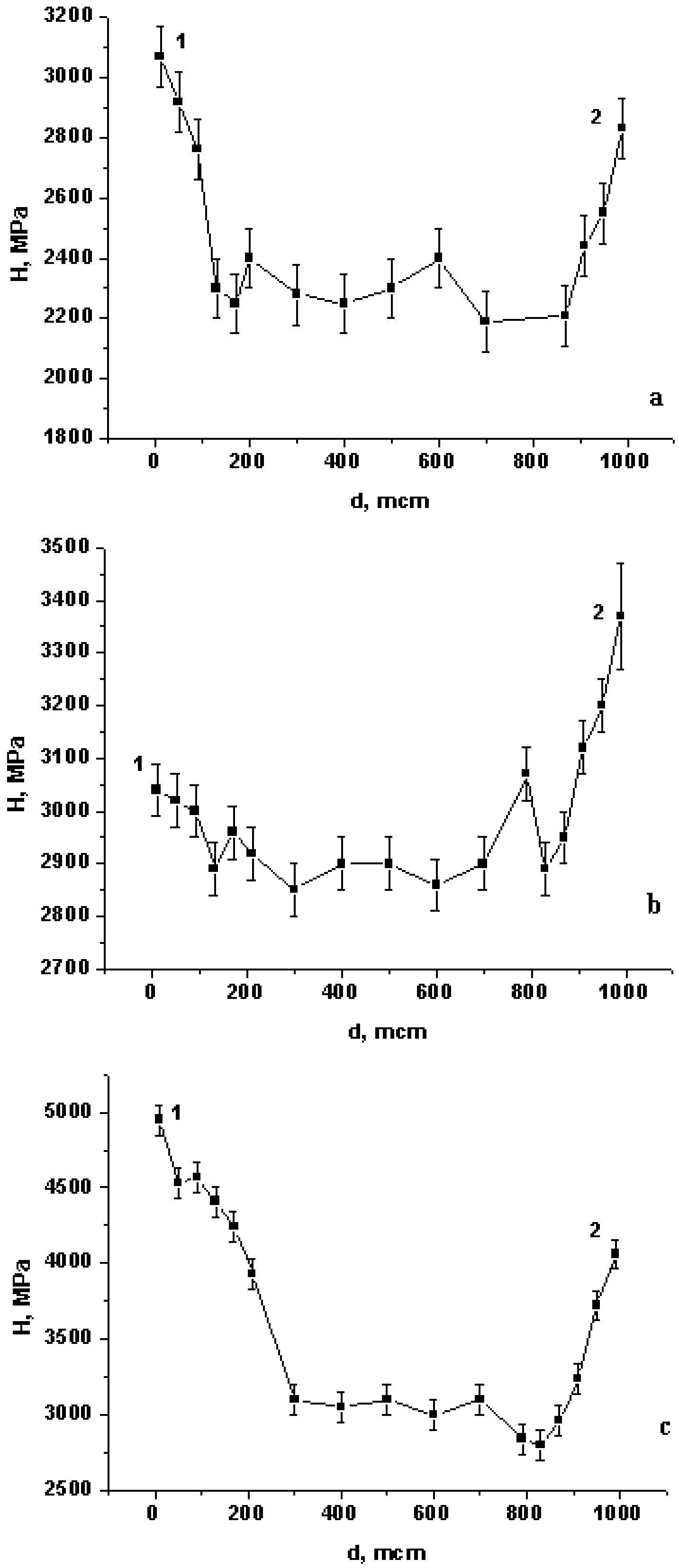
Visual analysis showed the melting in both the inside and the outside surfaces of the tube. It is seen that both the inside and the outside surfaces have a wavelike relief. There are a lot of droplets, influxes and ridges; the size of such relief fragments on the inside surface is remarkably larger than on the outside one. The farther from the irradiation source, the smaller the typical sizes of the elements of the surface relief. In other words, the surface relief in the "cold" end of the tube is smoother than in the "hot" end.

Part of the external surface of specimen #14 at the "cold" zone of the tube after 4-fold pulsed deuterium ion and plasma irradiations



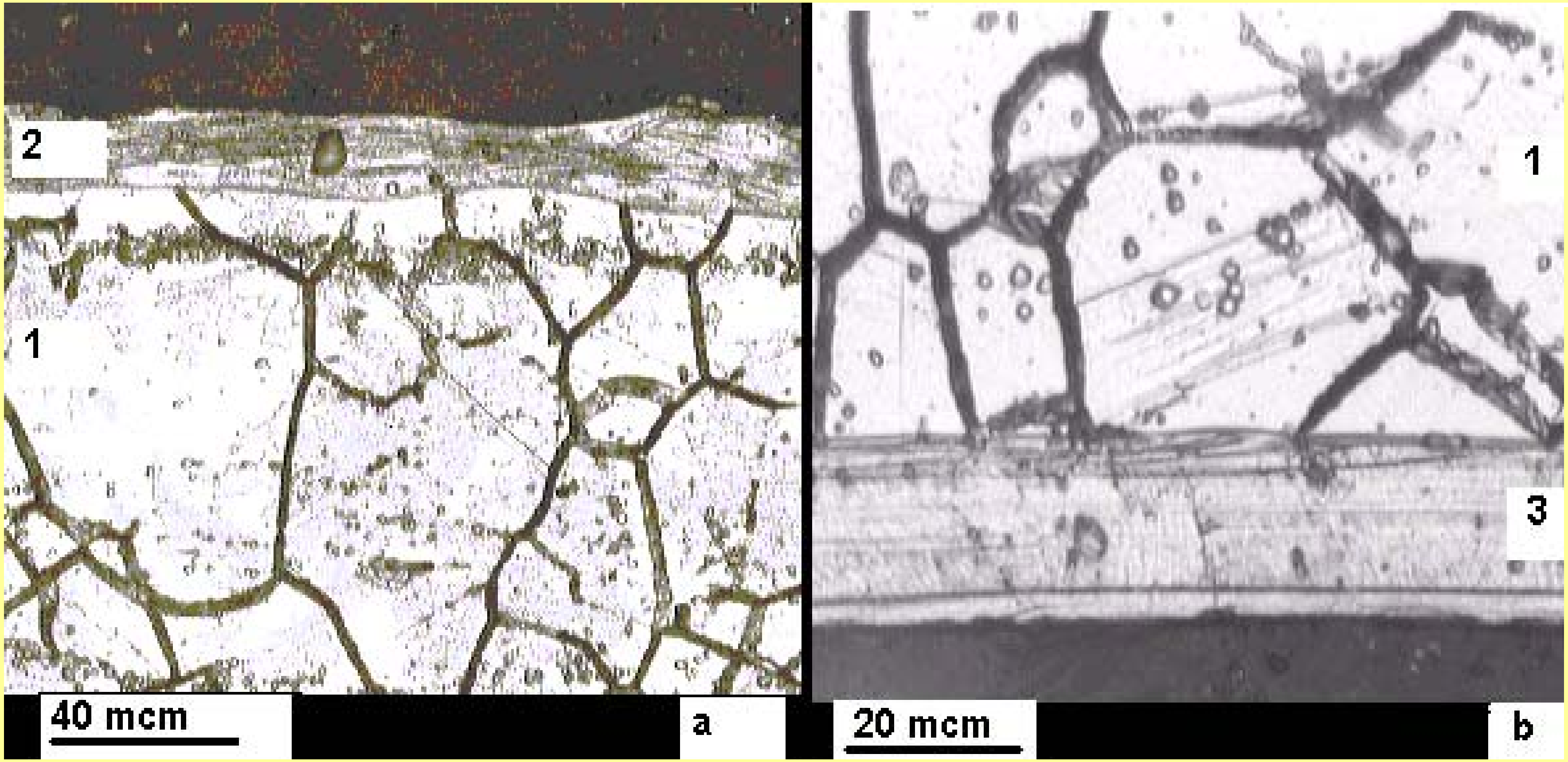
It is seen that on the outside surface of the "cold" part of the tube the structural defects are formed along closed curves. The form of the curves is close to a circle. The size of the circles corresponds to the grain sizes of the steel in the initial state (tens of micrometers). The growth of the bubbles occurred due to the evaporation of the manganese (as the most volatile element of the steel), as well as to the chemical compounds of deuterium with carbon and oxygen. Moving in the liquid phase to the high temperature zone, the bubbles were "frozen" on the irradiated surface as a result of fast crystallization

Changes of the micro-hardness in the specimens of the irradiated tube at the zone between the external surface layer (1) and the internal one (2): a – sample #1 (“hot”), b – sample #9 (“middle”), c – sample #15 (“cold”)



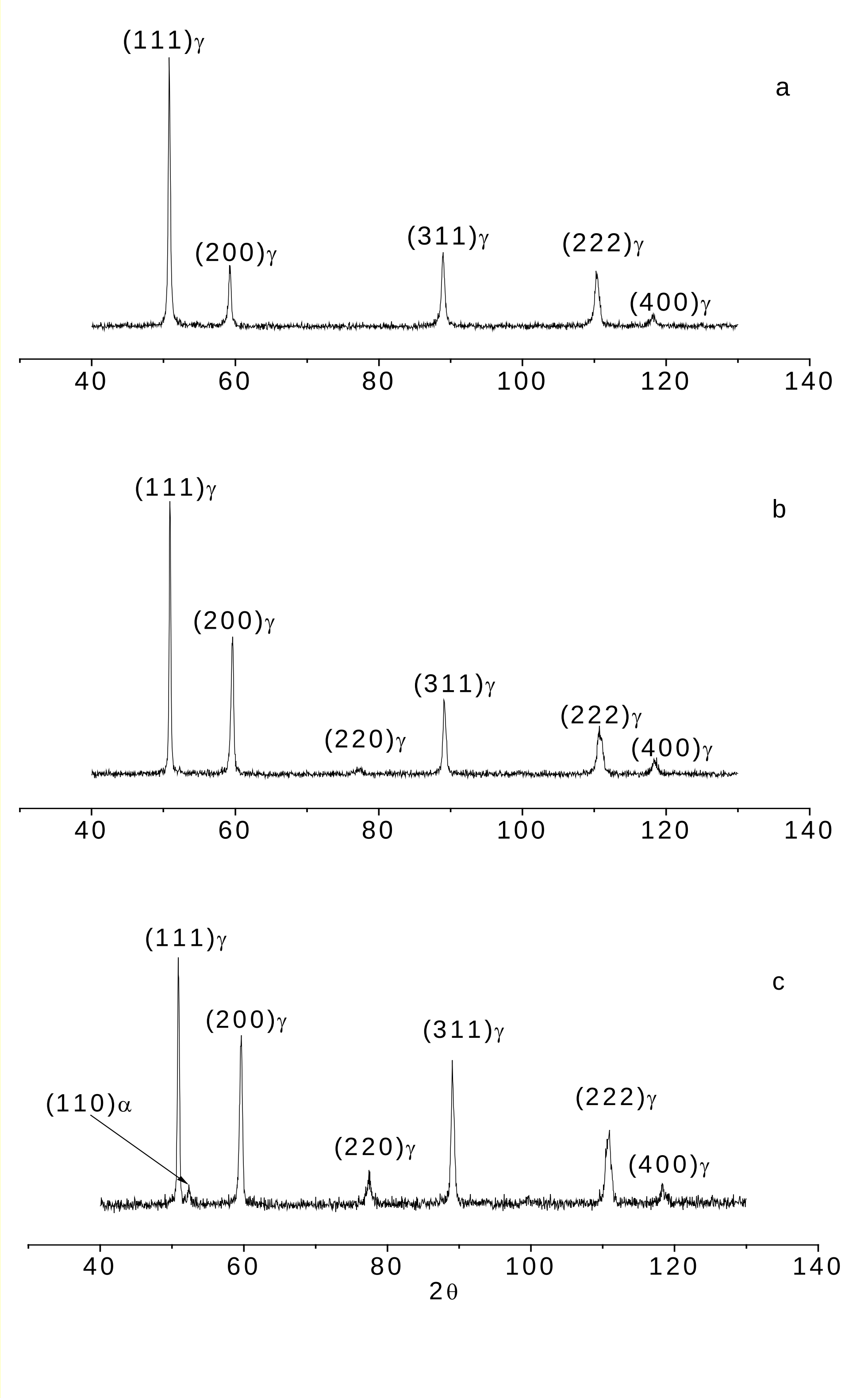
The Figures show that micro-hardness increases in the zones of outer and inner surface layers. Maximum values for H, as a rule, are observed in the surface layers. These results show that conditions of solidification and structure formations were different in the external and internal surface layers of the tube, as well as in different parts of the tube. X-ray diffraction analysis showed that the dispersible precipitations of the martrensite and α- phase were included in austenite matrix (γ-phase). Concentrations of the α- phase inclusions at the “cold” part of the tube were higher than at the “hot” one. The dispersible inclusions of the secondary phase, as a rule, induce hardening and strengthening of the surface layer.

Cross-sections of the steel tube at the central part after irradiation: a - specimen #8, b – specimen #9. 1 - initial microstructure; 2 – re-melted layer of the external surface; 3 – re-melted layer of the internal surface



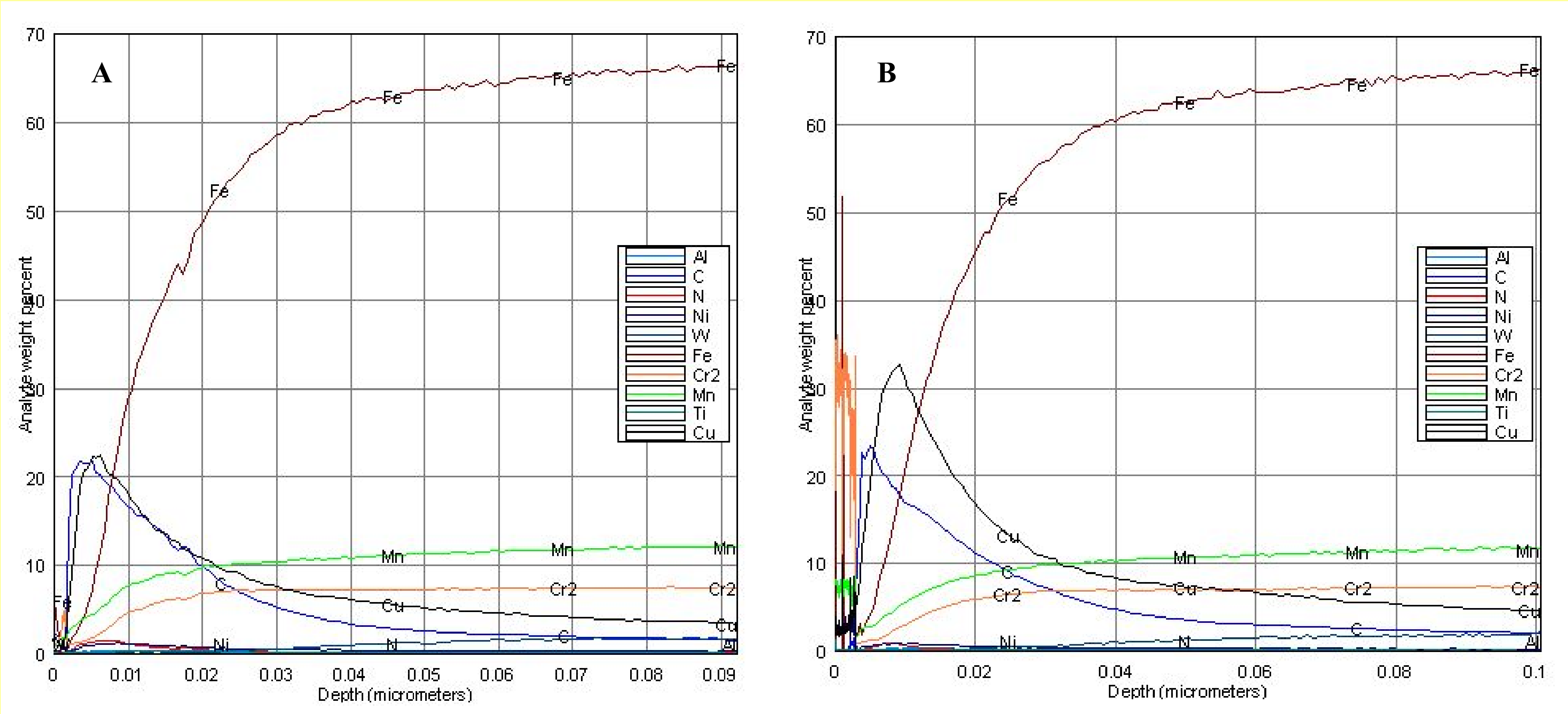
Hardening of the surface layers can be connected with the formation of a specific non- equilibrium microstructure of the steel (see Figure) under ultra-fast quenching of the liquid phase (with the speed of cooling ~ 10^8 - 10^9 K/c [4,5]). The volume content of the secondary phases was in the range of 1.5 - 3.0 % in the external surface layer and 5.0 – 9.5% in the internal one. It is obvious that conditions of pulsed plasma irradiation were essentially different on the external and internal surfaces of the steel tube: in the tube (as against "external" conditions) ions and plasma streams had no opportunity to dissipate within the chamber.

X-ray diffraction patterns for the irradiated steel tube at initial state (a) as well as at the external (b) and internal (c) surface layers of spec. #1



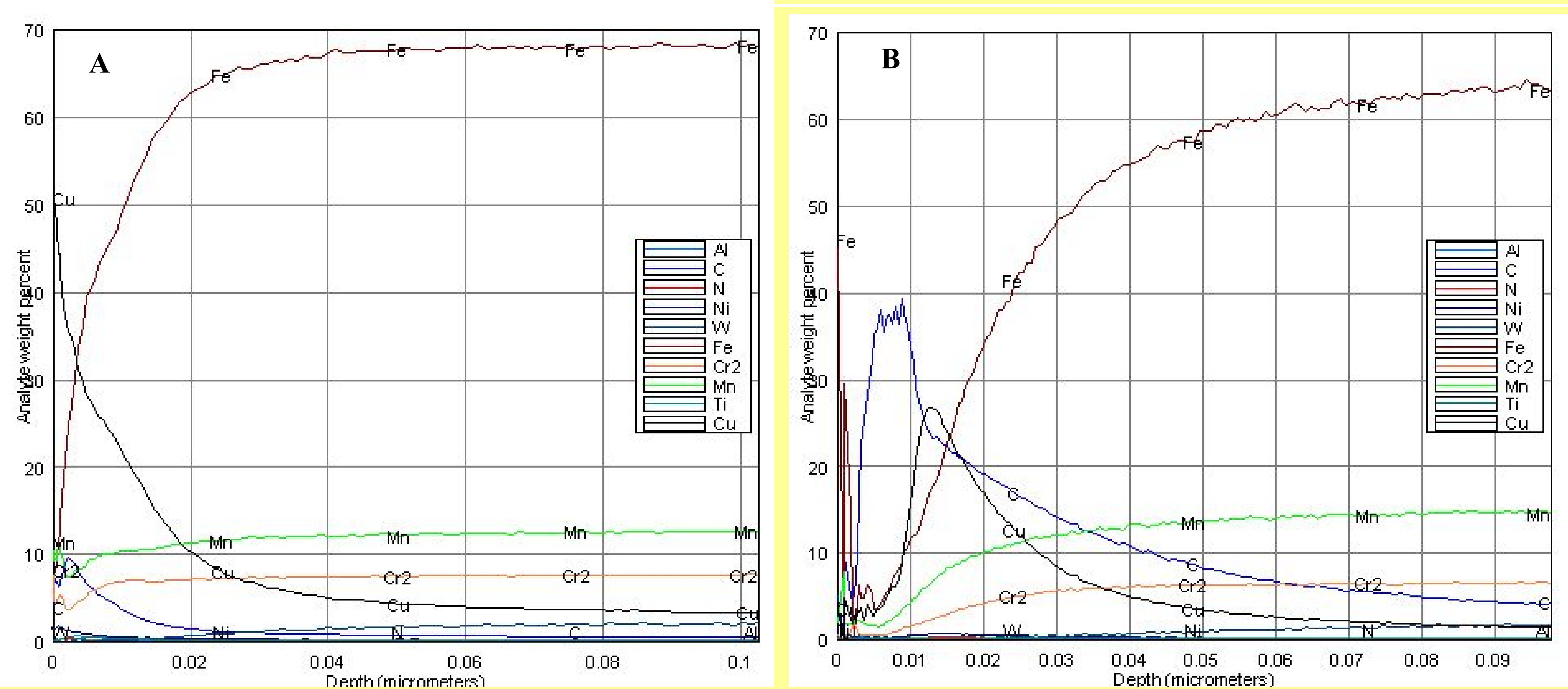
It is seen that the irradiation results in structure-phase transformation in the surface layers. In irradiated specimens we observe the reduction of (111)γ peaks and amplification of (200)γ peaks, appearance of the martensite and α-phase, as well as phase $Cu_{9.9}Fe_{0.1}$. The transformations observed are more significant at the internal surface layer compared to the external one.

Element content distribution near the external (A) and internal (B) surfaces of specimen #1 of the irradiated tube (atomic emission spectroscopy)



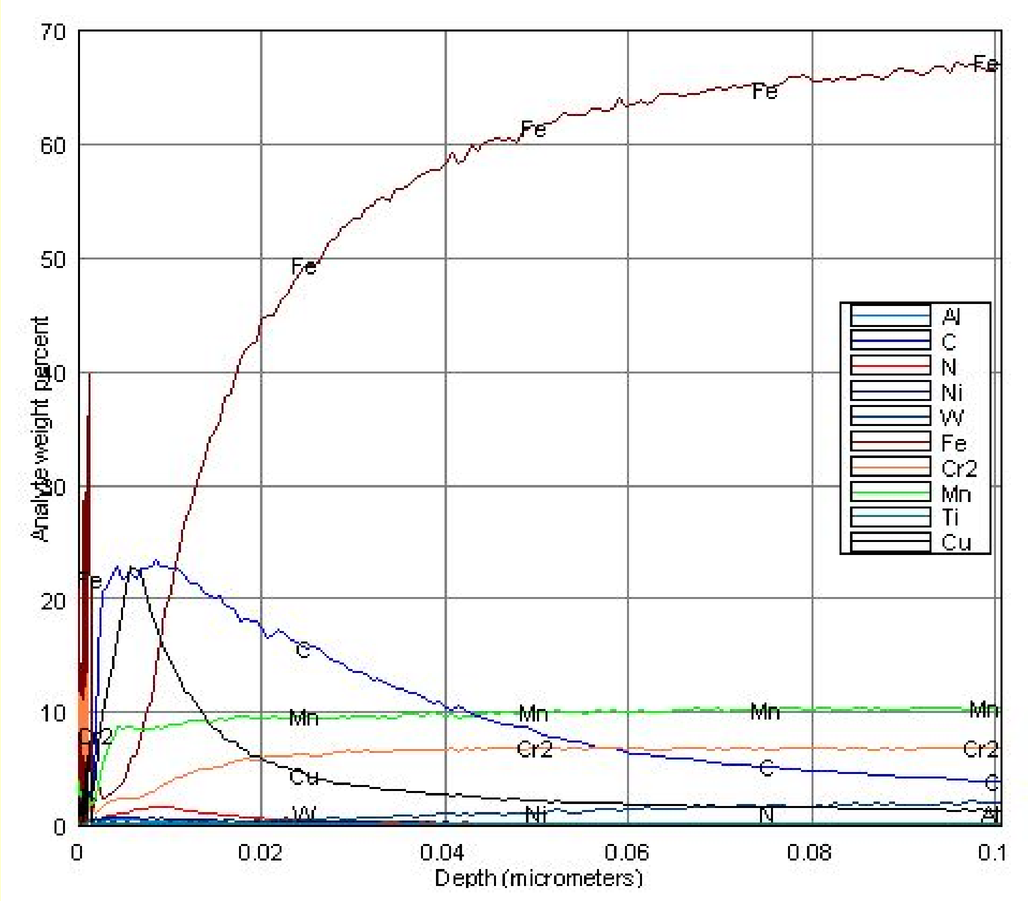
Concentrations of Fe, Cr and Mn decreased near the irradiated surface, while carbon, as well as copper contents, as a rule, remarkably increased with the approach to the irradiated surface. Besides Cu such elements as Ni and Ti (which were not present in the original steel) are present in the irradiated surface of the tube. The character of element distribution in the external and internal surface layers of the irradiated tube was about similar.

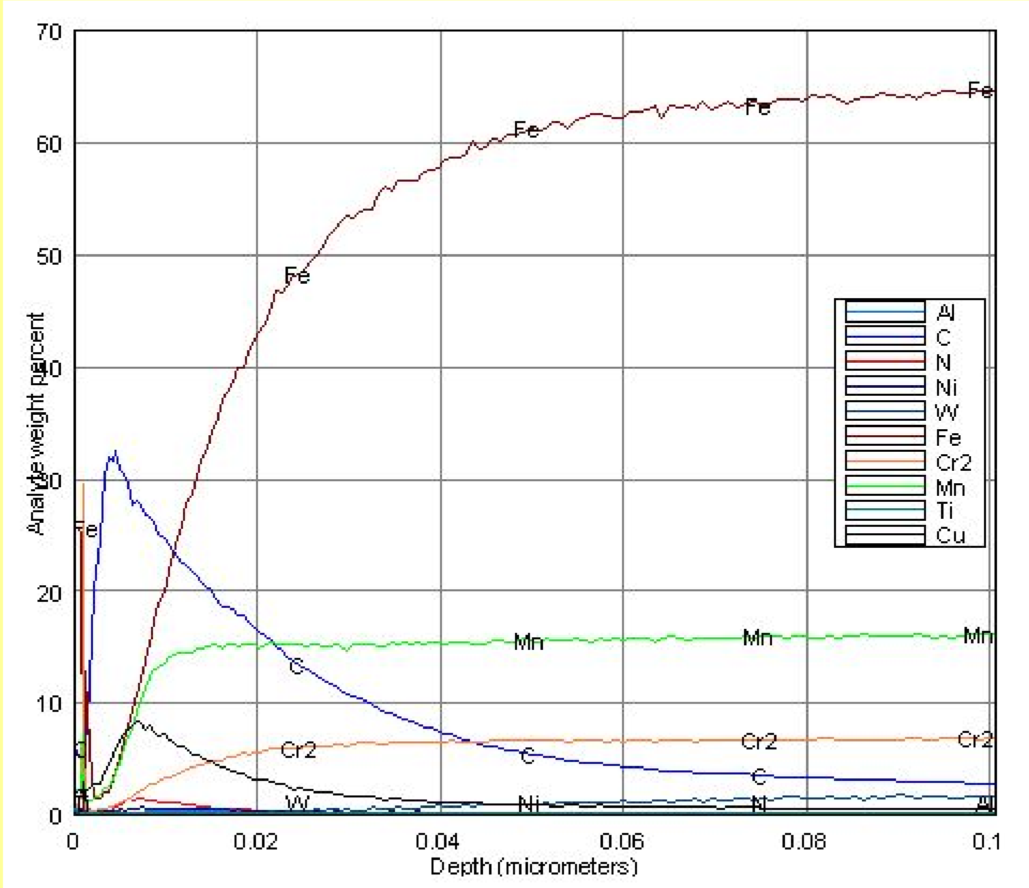
Element content distribution near the external (A) and internal (B) surfaces of specimen #5 of the irradiated tube (atomic emission spectroscopy)



It is seen that the character of element distribution at the external and internal surface layers of the irradiated tube in this specimen is about the same as in specimen #1.

Element content distribution near the external (A) and internal (B) surfaces of specimen #9 of the irradiated tube (atomic emission spectroscopy)





It is seen that the character of element distribution at the external and internal surface layers of the irradiated tube in this specimen is about the same as in specimens #1 and #5.

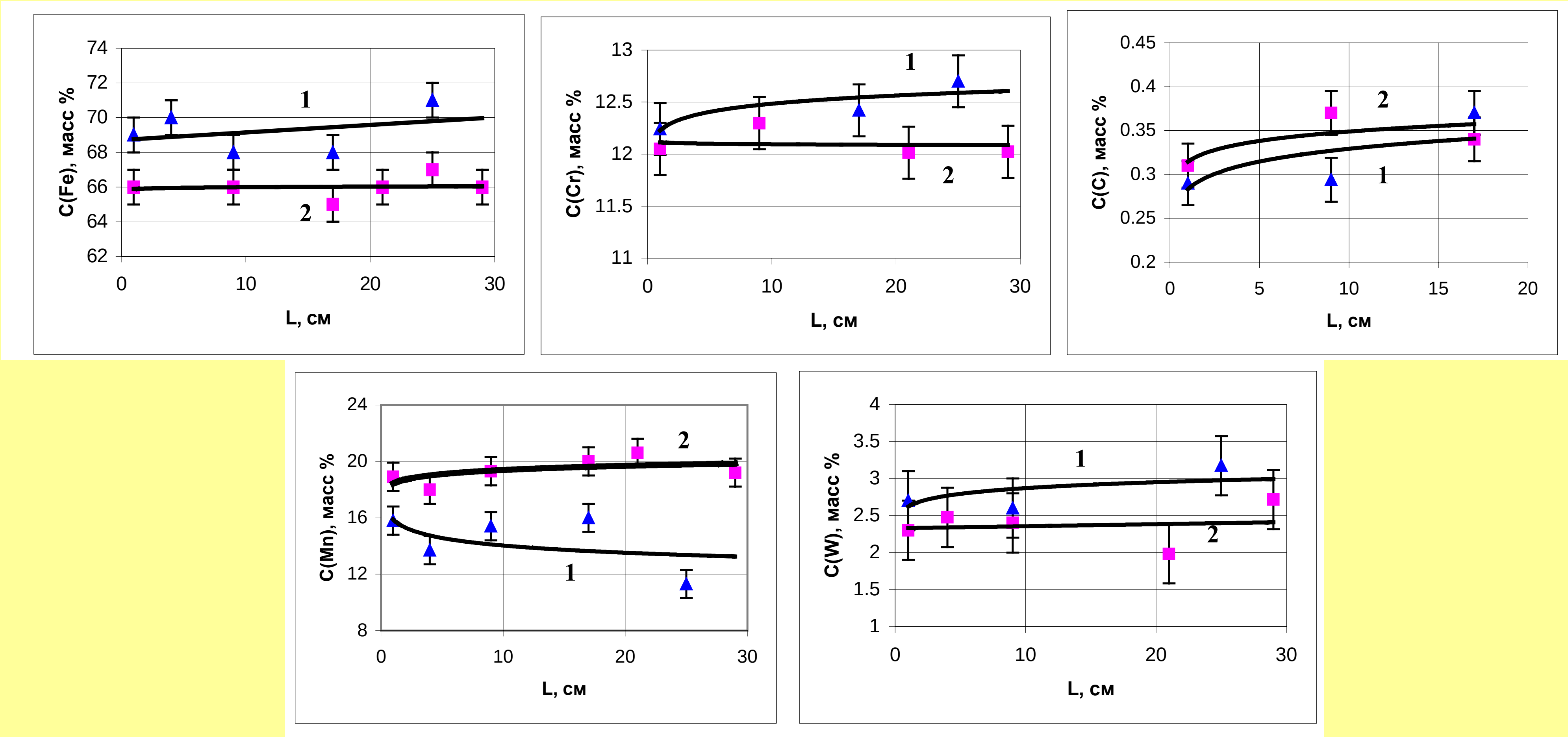
Analysis of the observed element distribution in the surface layers of the tube

The presence of Cu, Ni, Ti on the irradiated tube surfaces, as well as a high content of Cr in some parts of the tube, may be connected with evaporations of these elements from the functional materials of the PF chamber under the high-energy ion and plasma irradiation and their deposition onto the tube surfaces. The anode, which was manufactured of highly pure Cu, strongly evaporated under the high-energy electron beam. Ni, Ti and Cr were present in the steel cathode tubes, so these elements were evaporated under the ion and plasma pulsed irradiation [6 –9].

Copper, unlike Ni, Cr and Ti, deposited on the irradiated tube surface at an earlier stage while the tube surface was still in the liquid state. So the deposited copper after surface solidification was covered by the components of the cathode material (Ni, Ti, and Cr) deposited on the tube surface at the final stage of irradiation. Subsequent heating of the deuterium plasma enhanced Cu diffusion into the surface layers.

The maximum values on the curves of carbon distribution may be connected with two factors. The first factor is diffusion of carbon from the irradiated material to the surface in the non-uniform fields of temperatures and stresses. The steel crystalline lattice after pulsed plasma irradiation became stretched near the “surface layer – gas phase” interface and compressed in deeper layers. This enhanced carbon diffusion to the heated surface. The second factor is formation of bubbles filled with volatile CO and CO_2 compounds as well as compounds of carbon and implanted deuterium.

Elements content distribution along the external (1) and internal (2) re-malted surface layers of the irradiated tube



It is seen that concentration of iron on the external side was higher than the one for the internal side by 3 - 4 %. Concentration of the manganese on the external side of the irradiated tube was remarkably lower than concentration of Mn on the internal side, where it corresponded to the manganese content in the original steel. On the "hot" part of the tube this difference was ~4% and reached 7 - 8 % at the "cold" part of the tube. The selective evaporation of Mn at the surface of the tube reduced γ-phase stability and induced $\gamma \rightarrow \alpha$ transformation.

Conclusions

- The characteristics of the material damage, structural changes and elements distribution in the surface layer have been determined for the steel 25Cr12Mn20W hexahedral tube, which was placed in the cathode part of the Plasma Focus device PF-1000 along the chamber axis.
- It was established that irradiation of power density ~ 10^6 - 10^9 W/cm^2 led to melting, evaporation and sputtering of the surface material both on the internal and the external surfaces of the tube. The structural details, such as type of droplets, influxes and ridges on the internal surface of the tube were larger than the ones on the external surface.
- In the re-solidified surface layers the dispersible precipitations of the martensite, α-phase and phase $Cu_{9.9}Fe_{0.1}$ were observed in the austenitic (γ-phase) bulk. The volume content of the second phase was in the range of 1.5 – 3.0 % in the external surface layer and 5.0 – 9.5 % in the internal one. Such phase transformations induced hardening and strengthening of the surface layers. This effect was more obvious at the “cold” part of the tube.
- It was found that high-energy beams led to a redistribution of the steel components near the irradiated surface and to penetration of copper into the re-melted layer both on the internal and external surfaces of the tube. Concentrations of copper and carbon were the highest at the surface of the tube, but the content of iron, chromium and manganese decreased there.
- In an applied aspect the results obtained and the data of previous investigations showed an advantage of using Plasma Focus device to imitate the heat loading on the material under plasma disruption in a thermonuclear fusion reactor. Moreover, the possibility of using Plasma Focus device to modify a surface layer in the hard-to-reach parts such as internal surfaces of the tubes was demonstrated.

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