Initiation and Interaction of a Pulse Beam of Xenon Ions with an Obstacle

Viktor A. Morozov[1*], **Yuriy V. Petrov**[1**], **Anton A. Lukin**[1], **Viktor M. Kats**[1], **Vladimir A. Bratov**[1], **Sergei I. Fedoseenko**[1]

[1] Saint-Petersburg state university, 7-9, Universitetskaya nab., Russia

*viktor.morozov@math.spbu.ru, **yp@yp1004.spb.edu

Abstract

The concept of creating intense pulsed ion beam from source based on cryogenic target of inert gases (Xe) irradiated by intense electrons beam from the cathode with explosive emission in the nanosecond range was realized.

The studies were conducted on the modernized experimental equipment consisting of a short high- voltage pulse generator GKVI-300, high-vacuum pumping system based on turbo-molecular pump TMN-1000M with the ability to hold pressure in research chamber $\sim 1 \cdot 10^{-6}$ Torr, Gifford-McMahon cryocoolers MSMR-110-3, 2/20 with closed He – cycle that provides cooling temperature T=20K and a gas injection system.

Gas xenon (Xe 4,8, with the percentage of xenon 99,9988%) was used as working gas It ffreezes to copper anode plate cooled to a temperature of 45-50 K.

As a test materials were selected D16 aluminum alloy and stainless austenitic steel 12X18H10T (cryogenic constructional steel) having wide practical application.

Micro-topography surface and X-ray photoelectron spectra of samples were obtained at an atomic force microscope Solver PRO-M and the electron spectrometer ESCALAB-5 (line Kα Al (hν=1486.6 eV)) .

The impact of short-pulsed ion beam on a sample of D16 alloy and stainless steel 12X18H10T leads to erosion of the surface in the form of separate craters, the depth of which depends on the hardness of the material and the number of pulses. Uniform over the surface area distribution of craters can be achieved when placed in front of target fine-mesh nets of a refractory metal such as molybdenum.

A numerical simulation of fracture of aluminum target by a beam of high-energy ions, the finite element method, corresponding flow through one grid was realized. The results are in good agreement with experimental data.

Keywords: ion beam, electron beam, erosion, cryogenic target, computational modeling

1. Introduction

Influence of powerful short-time beam of particles – photons, electrons, ions – on physical and mechanical properties of constructional materials represents a great interest, both with theoretical, and from the practical point of view. It gains special relevance in connection with the technogenic accident which have occurred recently, especially on nuclear power plants where the processes caused by fast particles are extremely important. Influence is capable to modify significantly physical and chemical and mechanical properties of materials. The knowledge of mechanisms of changes of properties is extremely necessary as for an estimation of possible changes under the influence of particles, and in connection with prospects of creation of new functional materials and changes of characteristics in the necessary direction. Studying of influence of the ions having high energy, on constructional materials very important. Radiation bunch processing everything is wider and more widely applied to modifying of near-surface layers of parts that allows to improve considerably their operational characteristics [1]. The particular interest represents research of influence of the short-time beam having a number of features in relation to influence on physical and mechanical characteristics. The large number of the designs, allowing to receive ionic bunches with various parameters [2] is so far developed. However they represent rather difficult devices that does them extremely expensive. In this regard in this work researches on creation of the source, allowing to receive short-time, about 10-100 nanoseconds, a beam of ions of the high power which design has to be most adapted for the available equipment are conducted.

2. Experimental techniques

The main idea based on creation of a source of ions, consists in the following. The generator of short high-voltage impulses of GKVI-300 allows to receive a short-time pulse beam of the electrons having high energy. This beam can be directed on a material containing atoms of the necessary grade. This leads to a number of processes (thermal heating, an electronic and stimulated desorption, cascade ionization) and at a surface of the anode is formed the plasma consisting of electrons and ions of a various charges. These ions, being positively charged, move in the direction, return to electrons beam. It is a so-called passive source of ions. In our case the version of the cryogenic passive anode which allows to receive unicomponent structure of an ionic bunch is chosen.

When developing a design a number of the moments was considered. First, it is necessary that issue of electrons which in available strong electric fields has explosive character, didn't lead to changes on a surface of the sample which is a part of cathode assembly. Therefore the cathode was made compound. It represented a ring in which the sample (fig.1) took place.

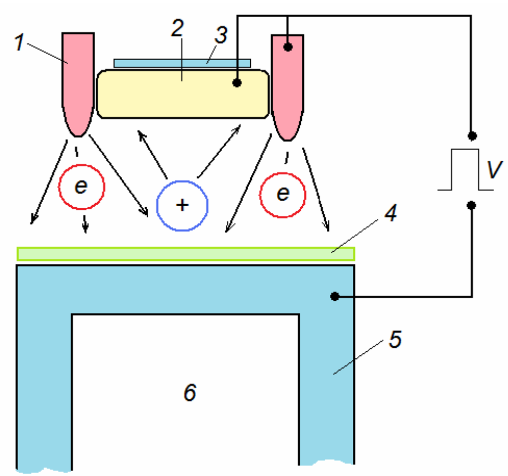


Fig. 1. Schematic image of a source of ions. 1 – cathod ring, 2 – a sample, 3 – a reflecting layer for registration of mechanical stress by an interferometric method, 4 - a layer of the condensed inert gas, 5 – the anode, 6 – the volume cooled by the cryorefrigerator.

Edges of a ring 1 have the pointed form and protrude from the sample 2. When giving a high-voltage impulse electron emission happens from a ring edge as such geometrical form provides the greatest intensity of electric field in this place. The sample thus doesn't participate in formation of an electronic beam. The back party of a sample is polished to mirror shine and serves as an informative mirror of the interferometer of Michelson by means of which shift of this surface is measured. Shift arises owing to impact on a sample of an ionic beam. In the ring cathode there are openings for leading of a laser beam of the interferometer.

The second important point belongs to an anode material. At impact of ions on a solid body it is important that there was no chemical interaction between ions and atoms of a material. Otherwise it can lead to change not only mechanical and structural properties, but also to change of a chemical composition. In this regard ions of inert atoms are the most suitable. As that xenon was chosen. The choice was dictated by possibility of condensation of this gas when cooling anode. For this purpose the anode was carried out in the form of a rod 5 cooled by system, consisting of compressor installation with the control and management block and a cooler. Such system allows to receive the xenon layer which thickness is defined by pressure of gas filled through a inlet valve and hold time on an anode surface. After achievement of a layer of the necessary thickness xenon is pumped out up to the pressure ~ 10^{-6} Tor. Such sequence of actions provides localization of a place of formation of ions. Ionization of atoms of xenon takes place only in close proximity to an anode surface. Besides, in high vacuum length of run of particles considerably exceeds an available interval between the anode and the cathode. It means that dispersion of ions in such conditions is negligible.

2.1. Experimental unit

Researches were conducted on the modernized experimental unit consisting of the generator of short high-voltage impulses of GKVI-300, the research camera which appearance is given on Fig. 2, high-vacuum pumping system, MCMP-110-3,2/20 Gifford-Makmagona cryorefrigerator with closed He – cycle providing temperature of cooling of $T_{coll}=20\ K$ and gases inlet system.

Fig. 2. Appearance of the research camera and gases inlet system .

Appearance of the block of a cooler and cooling head is given on Fig. 3.

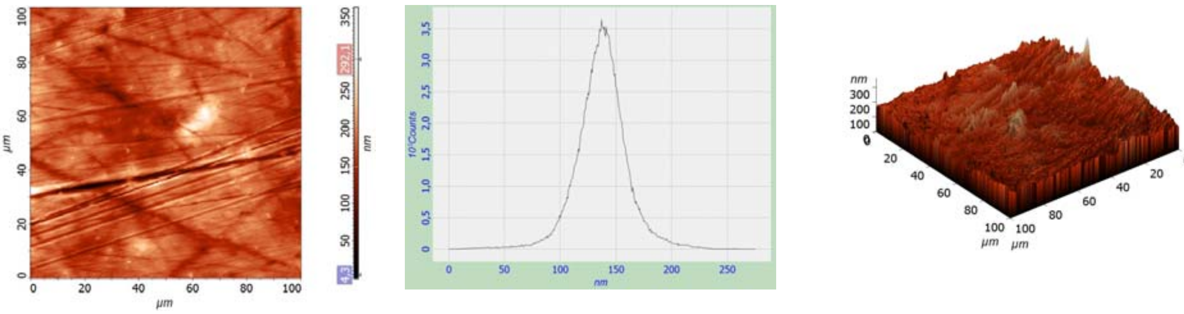
(a) (b)

Fig. 3. Appearance of the block of a cooler (a) and cooling head (b).

Air pumping from the research camera was carried out by means of the turbomolecular pump TMN-1000M, for the purpose of an exception of vapors of oil in it. Thus working pressure in the research camera made ~ $1\cdot10^{-6}$ Tor.

As studied constructional materials the aluminum alloy of D16 and stainless steel of an austenitic class 12X18H10T (steel constructional cryogenic), having broad practical application were chosen.

Samples represented disks with a diameter of 7 mm and 3 mm high. Flat surfaces of disks were ground and polished from two parties to mirror shine. The typical micrograph of a surface measured by means of a atomic force microscope Solver PRO-M, is given on Fig. 4. The average size of a roughness of a surface on a site with sizes of 100x100 microns didn't exceed 170 nanometers



(a) (b) (c)

Fig. 4. Micrograph of a surface of a sample from D16 alloy: (a) - the two-dimensional image of a surface in brightness scale; (b) – average roughness of a surface; (c) – three-dimensional image of a surface.

When carrying out researches various options of placement of samples in the ring cylindrical cathode with explosive issue were used. This cathode took place in the removable cathode assembly shown on Fig. 5.

Fig. 5. Appearance of removable cathode assembly with explosive emission: 1 – ring cylindrical cathode; 2 – sample.

2.2. Parameters of an exciting pulse electronic beam

In the process of researches on studying of influence of intensive streams of ions of small duration on constructional materials the pulse heavy-current accelerator of electrons with average energy of electrons in a range 250 keV was used. Characteristic oscillograms of impulses of voltage and the current, measured at discharge on a cryotarget, are given in Fig.6. Amplitude of impulses of voltage made ~ 250 kV. Duration of impulses of voltage made ~ 40 nanoseconds. Assessment of amplitude of an impulse of current ~ 9.5 kA at distance the cathode anode ~ 5 mm.

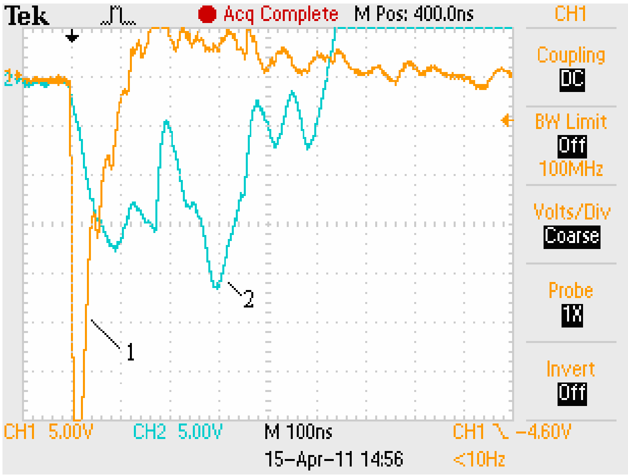
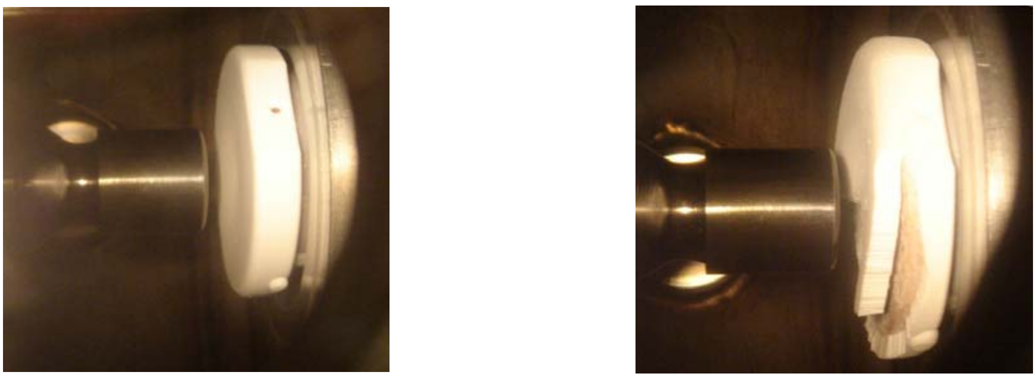


Fig. 6. Characteristic forms of oscillograms of impulses of current and voltage at direct release of an electronic beam on the cryotarget/anode from firm inert gas (Xe): 1 – voltage impulse (relative units), 2 – a current impulse (relative units).

2.3. Cryotarget/anode formation from firm inert gases (Xe)

As the working gas which is freezing condensing at cooling of a copper anode plate (Fig.3) up to the temperature of 45 - 50 K, was used gas xenon (Xe 4.8, with percentage of xenon 99,9988 %). At such temperature all gases, except for helium, hydrogen and neon are condensed. Freezing / xenon condensation on the cooled copper plate of the anode was conducted for filling in the research



(a) (b)

Fig. 7. Cryotarget/anode photos with condensed layer of solid xenon: (a) – an initial layer; (b) – a type of a target after a splitting off.

camera xenon gas. The photo of a thin frozen layer of Xe is provided on Figs. 7(a).
At target radiation by a powerful high-voltage impulse of electrons in the center of a target the crater by diameter ~ 10 mm is formed. At repeated radiation such target needs to be restored, i.e. freez in the target center a new layer of Xe by a repeated blousing of xenon and to sustain necessary time (~ 10 min.). At rather thick layer of xenon in the process of discharge the splitting off of part of a layer, as shown in Figs is observed. 7. It is visible that the condensed layer of xenon possesses crystal structure. By a visual assessment thickness of a layer of xenon, frozen within 1 hour, made ~ 3 mm.

3. The experimental results

3.1. Radiation by an ionic bunch of samples from D16 alloy

At radiation by an ionic beam of samples from an alloy of D16 the following geometry of an arrangement of a sample in the cathode was used. Before a sample at distance of 1 mm the molybdenic grid with optical transparency of ~80% (3 lines/mm, thickness of Mo wire of 40 microns), welded on a ring from stainless steel 12X18H10T 1 mm thick was established. This sample was subjected to influence of five consecutive impulses of ions of Xe. Results of such impact are given in Fig.8.

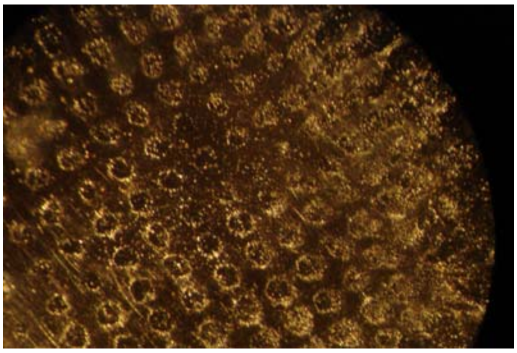


Fig. 8. The photo of a surface of a sample from an alloy of D16 subjected to influence of five impulses of ions of xenon through a molybdenic grid.

It is visible that on a surface of a sample accurately expressed regular relief from hollows (craters) and hills with approximately identical sizes is observed: width of hollows (craters) is equal ~ 180 microns, and width of hills ~ 160 microns. Thus distribution of intensity of a beam almost uniform on all area of a sample with primary concentration in the center of sample with a diameter about 3 mm, i.e. at the set configuration of cathodic knot is observed focusing of an ionic beam.
There is a probability of formation of craters at the expense of sample bombing by "spalls" microparticles from a firm xenon target which can arise because of a powerful irradiating impulse of electrons. To confirm or exclude such opportunity, experiment on sample radiation by an ionic bunch of xenon through an aluminum foil 10 microns thick was put. It was expected that in case of bombing by " spalls " microparticles of the xenon which is taking off from the cryotarget/anode with a huge speed, the aluminum foil will be punched and will contain a set of microopenings which can be registered by means of a nuclear and power microscope. As a result of such experiment the aluminum foil simply "exploded": the melted drop of a foil appeared on a sample surface, and on a copper plate of the anode drops of the melted aluminum were observed when defrosting target, as shown in Fig.9. The received result can be explained only with interaction of ions with an aluminum target, but not bombing by microparticles.

Fig. 9. The cryotarget/anode photo when defrosting after radiation of an aluminum foil (thickness of 10 microns) a powerful impulse of ions.

3.2. Radiation by an ionic beam of samples from stainless steel 12X18H10T

Experiments on radiation of samples were executed by a powerful pulse bunch of ions of xenon from stainless steel in the same geometry, as well as at impact on D16 alloy. Symmetric distribution of influence and the relief of a surface consisting of hollows and heights is here too observed, coincides with received earlier for samples from an aluminum alloy (Figs. 10).

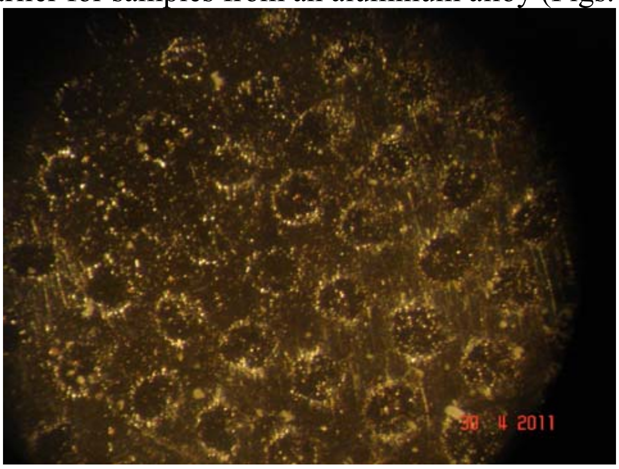


Fig.10. The photo of a surface of a sample from stainless steel 12X18H10T after radiation by a pulse beam of ions of xenon.

4. Numerical modeling of process of destruction of an aluminum sample

When carrying out experiment the bunch of ions was passed through a molybdenic grid with a cell size ~ 250x250μm^2. On an aluminum sample craters with sizes ~ 180 µm opposite to each cell of a grid are found. Let's consider the task corresponding to impact on a sample of a stream of ions, passing through one cell of a grid. In experiment it is possible to define the energy transferred to a sample by a stream, passing through one cell of a grid. Further, we replace impact of this stream on a sample with blow to a sample of the aluminum cylinder with a diameter of 60 microns and length corresponding to duration of influence (80-100 nanoseconds). Speed of the cylinder we choose from compliance of energy of the hammer of energy of a beam of the ions passing through one cell of a

molybdenic grid. When carrying out numerical modeling the developed approach [3-5], allowing to integrate criterion of incubation time into numerical schemes on the basis of a method of final elements was applied. For the solution of a task the finite element ANSYS [6] package was used.
The following parameters of a target, characteristic for aluminum were chosen: density – 2700 kg/m^3, the Young's modulus – $6.65 \cdot 10^{10}$ Pa, Poisson's ratio – 0.34, critical stress on a gap – $3 \cdot 10^8$ Pa, the structural size – 15 microns, target thickness – 3 mm. The hammer material on properties corresponds to a target material. Diameter of the hammer – 60 microns, height – 90 microns. hammer speed at the time of the contact beginning – 650 m/s.
After completion of modeling the zone in which there was a material division was investigated. On a fig. 11 the type of a sample after completion of modeling is presented. On a fig. 12 on not deformed sample knots in which there was a destruction are noted.

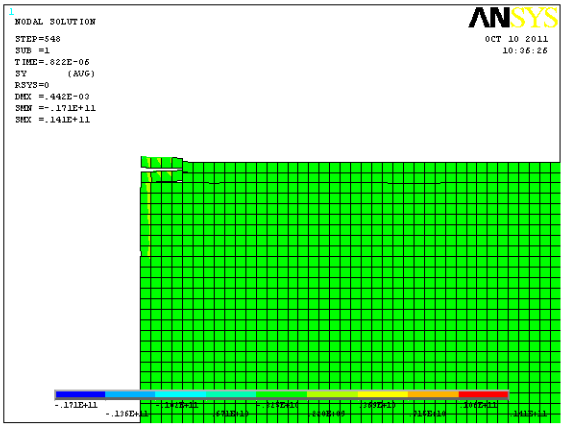


Fig. 11. Type of a sample after completion of modeling.

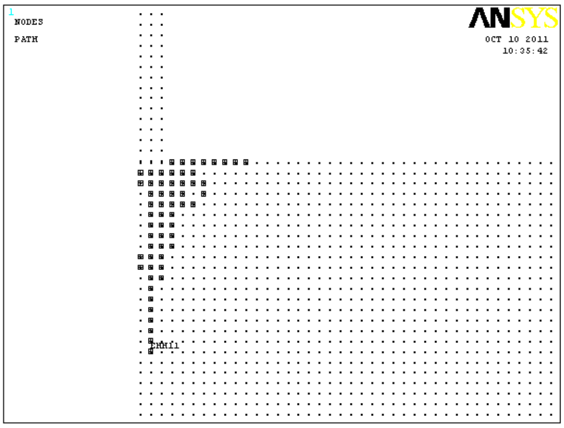


Figure 12. Node in which there was a destruction.

The size of the stamp formed on an irradiated surface, received as a result of numerical modeling coincides with observed in experiment. The received results speak about applicability of the developed approach for a prediction of destruction of the samples loaded by a stream of high-energy heavy ions.

5. Conclusion

On the basis of the conducted research on influence of intensive streams of ions (xenon) of small duration on physical and mechanical properties of constructional materials it is possible to draw the following conclusions:
1. The concept of creation of an intensive pulse source of ions on the basis of a cryotarget from solid inert gases (xenon) is realized at radiation by its powerful impulse of electrons from the cathode with explosive issue in the nanosecond range.
2. Impact of a short-time pulse ionic beam on samples from an alloy of D16 and stainless steel 12X18H10T leads to a surface erosion in the form of the separate craters which depth depends on the hardness of a material and quantity of impulses.
3. The measured parameters of craters on a surface of samples give the chance to formulate initial and boundary conditions in mathematical model for calculation of influence of intensive streams of ions of small duration on physical and mechanical properties of constructional materials.
4. Results of the carried-out numerical modeling of process of destruction of an aluminum target under the influence of a beam of high-energy ions by a method of final elements well coordinated with data of experiments.

References

[1] B.A.Kalin, Radiation beam technologies of processing of constructional material. Physics and Chemistry of Materials Treatment, 4 (2001) 5-16.

[2] V.M.Bystritsky, G.A. Mesyats, Ya.E.Krasik, Powerful pulse sources of ions, Physics of elementary particles and atomic nucleus, 22 (1991) 1171-1198.

[3] V. Bratov, Yu.Petrov, Application of incubation time approach to simulate dynamic crack propagation. International Journal of Fracture, 146 (2007) 53-60.

[4] V. Bratov, Yu. Petrov, Optimizing energy input for fracture by analysis of the energy required to initiate dynamic mode I crack growth, International Journal of Solids and Structures, 44 (2007) 2371-2380.

[5] V. Bratov, Yu.Petrov, Application of incubation time approach to description dynamic crack propagation. Doklady Akademii Nauk, 416 (2007) 624-626.

[6] ANSYS. User's Guide, Release 11.0 ANSYS Inc., Pennsylvania, USA, 2006.