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Action of Shocks Generated in Solid Targets by Dense Plasma Focus Devices and at Pulsed Laser Irradiation

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Abstract

Shock waves actions upon materials perspective for using in future thermonuclear fusion reactors are investigated experimentally and by means of numerical modelling. The shocks are generated by powerful streams of plasma and fast ions in Dense Plasma Focus devices as well as by irradiation with a laser operating in a Q-spoiled mode. Power flux densities of these streams on the targets' surfaces are in the range 10^{14} – 10^{16} W/m^2. They are used for tests of the above materials, and their influences are compared for a number of substances. It is shown that in the above-mentioned identical conditions Plasma Foci generate shock waves with amplitudes of approximately two times higher than that for the laser case. Fronts of the shocks are formed here faster than at the laser irradiation. A simple analytical formula for calculations of the amplitudes of shock waves in radiation material science experiments provided with Dense Plasma Focus devices are advanced.

Keywords: Dense Plasma Focus, laser radiation, shock wave, plasma facing materials, numerical modelling

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1. Introduction

The construction phase of large nuclear fusion facilities ITER (France), LMJ (France), NIF (USA) and Iskra (RF), which belong to both approaches to controlled nuclear fusion exploiting inertial and magnetic plasma confinement, is in visible progress. These recent developments in fusion pave is a clear path for the forthcoming physics and technology research activities, which are still required for the successful construction and operation of the present-day main-stream fusion facilities and DEMO fusion power plants.

One of the key issues still to be resolved in the quest for fusion energy production is the characterization, qualification (testing) and development of advanced plasma facing materials capable of withstanding the extreme radiation and heat loads expected in fusion reactors (FR). Fundamental understanding of plasma/beams-wall interaction processes in mainstream fusion devices requires dedicated R&D activity in plasma simulators used in close connection with material characterization facilities as well as with theory and modelling accomplishments.

Dense Plasma Focus (DPF) devices [1] are a very good tool for verification of dissimilar candidate materials counted as the perspective ones for the elements of fusion chambers subjected to powerful radiations (first wall, divertors, etc.) [2]. These devices are used for irradiation of specimens with powerful pulses of the radiations of two types – hot plasma streams (velocities v = (2-3)×10^5 m/s) and fast ion beams (energy $E_i \sim 100$ keV) – with power flux density up to $P \sim 10^{16}$ W/m^2, and with a pulse duration in the range of 10 – 100 ns to simulate conditions, expected in the chambers of FR with the Inertial Plasma Confinement (IPC) as well as with the Magnetic Plasma Confinement (MPC) during emergency situations (ELMs, VDE, disruptions). Besides an Nd-glass laser operating in a Q-spoiled regime (with about the same power flux density as the stream of fast ions in DPF – $P \sim 10^{16}$ W/m^2) has been used for irradiation of similar specimens of the same materials.

Comparative researches of radiation resistance of the materials that were subjected to the action of the above-mentioned streams generated in a DPF and of laser radiation have been undertaken.

It is known that under high energy density on the target's surface (approximately > 10^{15} W/m^2) various types of radiation may produce in a bulk of materials shock waves (SW) [3]. Their passage through material results in changes of its structure and properties becoming apparent on micro- and macro-levels. In the first case within the SW front different types of point and linear defects are formed (vacations, cascades of vacations, Frenkel pairs, dislocations, dislocation bunches, etc.) and polymorphic transformations take place [4 - 8]. In the second case one may observe specific "long-range macro-effects" [9 - 11]. They include anomalously high mass transfer in the direction of the vector of the incoming energy stream, creation of centers of the dynamic damage of material, destruction of the back side of the sample-target by chipping its off, etc.

The main purpose of the work is an analytical investigation of the samples irradiated in different devices, and numerical simulation of the physical processes taking place during the samples' irradiation in the bulk of materials. Generally (see, e.g. [2, 10 – 13]) morphology of damage characteristics, phase, elemental and structure changes of samples after irradiation, tribological characteristics of them, etc. were investigated. It was obtained: (i) a data base of bulk damages behavior of selected materials under different heat and particle load conditions and various sample treatment scenarios, and (ii) it was provided a comprehensive analysis of plasma-surface interaction processes under intense fusion-relevant pulses irradiated the samples. This paper presents some results on production and passage inside substance a shock wave obtaining an evolution of its parameters on the way. Presented here method of numerical modelling of SW in material is developing a concept proposed in the work [12].

2. Devices and irradiation conditions

2.1. Devices

Dense Plasma Focus devices PF-5M (2 kJ) and Vikhr' (6 kJ) (IMET RAN, Moscow, RF) and PF-1000U (1 MJ) and PF-6 (6 kJ) (IPPLM, Warsaw, Poland) working with hydrogen, deuterium, helium and with other gases were used to contribute to the knowledge-based understanding of the performance and adequacy of FR candidate plasma facing materials. Fig. 1 represents one of them – the "Vikhr'" device during its shot. Laser GOS-1001 used in the experiments was based Nd-glass. It operates in Q-spoiled mode. Usually these devices, independently on their bank energy, are able to produce equal power flux densities on a target's surface – yet with strongly different area values.

Charging voltage of the DPF capacitor banks was in the range 10-20 kV. Initial pressure of working gases used was in the range $10^2 – 10^4$ Pa. Amplitudes of a DPF discharge current were in the limits 0.2 – 1.0 MA.

These devices have been used for irradiation of specimens placed at different distances from the anodes of the DPF chambers and with various diameters of the plasma/fast ion streams and the laser focal spots.

In these experiments mainly different tungsten grades and coatings were tested, but also molybdenum, austenitic and ferritic steels, CFC, SiC and some others. Samples of the materials were usually 10×10 mm^2.

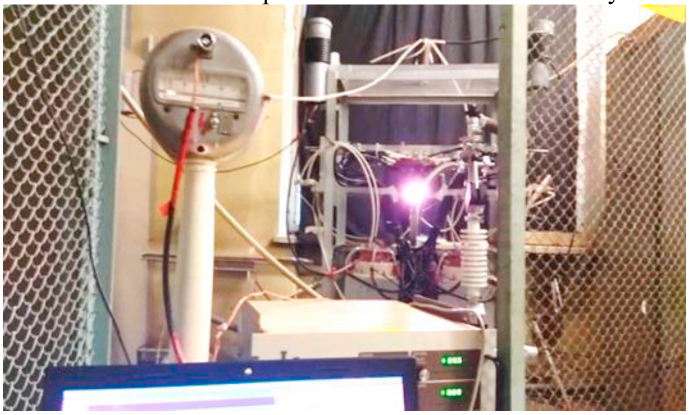


Fig. 1. The "Vikhr'" device during its shot.

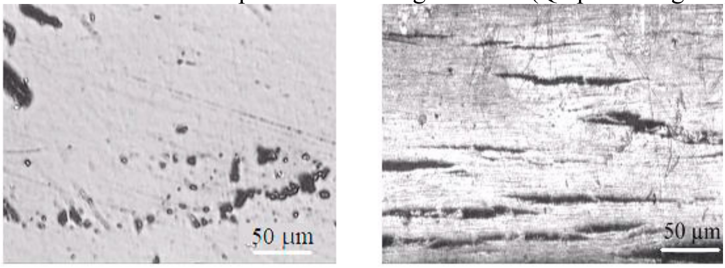
2.2. Irradiation conditions

Power flux densities of radiations on the samples' surfaces covering the values $\leqslant 10^{14}$ W/m^2 for plasma streams, to the extent of 10^{16} W/m^2 for fast ion beams [13] and in the range 10^{15} – 10^{17} W/m^2 for laser radiation in a Q-spoiled mode of the Nd-glass laser operation were exploited. Pulse durations were around 50 ns for all irradiation types. The irradiated areas were about $10^{-6} – 10^{-8}$ m^2 for laser beams, $10^{-5} – 10^{-6}$ m^2 for fast ion beams and the whole surface area of a sample for the plasma streams (10^{-4} m^2) in DPF devices [2].

Dissimilar number of shots (in the range $N = 2 – 50$) was applied. Distances from an anode to a target were in the limits from 3.5 cm till 50 cm.

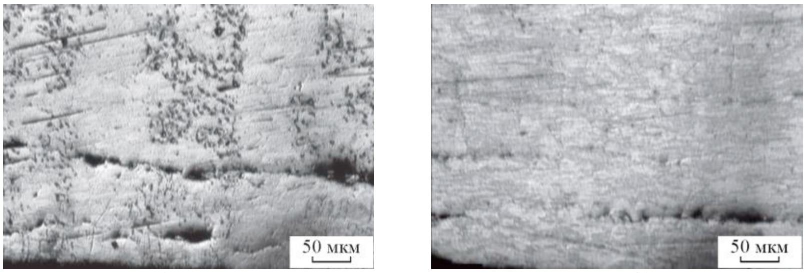
3. Experiments

Experiments have shown that after even a single pulse action upon a target of powerful streams of fast ions in a DPF or at a stroke of it from a laser operating in a Q-spoiled mode with power flux density on its face higher than 10^{15} W/m^2 one may observe microcracks in the bulk of the material under irradiation that are oriented approximately in parallel to the surface. The depth of these damages is more than 200 µm, which is much higher compared with the projective ion range (for the most representative deuterons with energy $E_d \sim 100$ keV it is equal approximately to 100 nm [14] whereas laser radiation is absorbed on the length of about a wavelength of it: $\lambda = 1.06$ µm). In Fig. 2 and 3 one may see SEM micrographs of cross-sections of Mo and W targets before and after actions upon them of powerful streams of fast ions in DPF and laser pulses from Nd-glass laser (Q-spoiled regime).



a) b)

Fig. 2. SEM image of the microstructure of the cross sections of Mo plate in the initial state (*a*) and in the zone of maximum irradiation intensity after its treatment in the DPF PF-1000U facility at a distance of 12 cm from the anode face ($q_i \approx 10^{11} – 10^{12}$ W/cm^2, $\tau_i \approx 10 – 50$ ns) (*b*).



a) b)

Fig. 3. The SEM picture of the cross-section of W sample after the action of laser radiation in Q-switched mode (*a*) and after its irradiation with deuterium and deuterium fast ion fluxes in the PF-1000U device (*b*).

During the time period of the phenomenon in a DPF known as a disruption of a current [1] the very powerful streams of fast ions with the above-mentioned ion energy and power flux density may act upon the target's surface [13]. Due to this irradiation secondary plasma is produced near the surface that has temperature $T_{s.pl.} \approx$ 50-100 eV and pressure up to 100 GPa [12, 13]. About the same phenomenon may be observed at the laser irradiation of a target [2] when it is operated in a Q-spoiled mode. Namely this high pressure action upon a target results in a generation of a SW and in its passage deep into the bulk of the sample. These SWs penetrating into the material help to stress (to emphasize) initial imperfections presented inside the virgin samples (like in Fig. 2*a*) and produced during their manufacturing. They are manifested in a manner that is seen in a depth of material (Fig. 2*b* and 3*a, b*).

4. Numerical simulations

4.1. Modelling of the interaction of the powerful stream of fast ions with a solid target

Calculation method of the paper is based on a theoretical model presented in the work [12] with addition of a state equation for cold matter. At the selection of the equation of state the shock (Hugoniot) adiabat as well as Mie-Grüneisen and Murnaghan relationships [14 -16] were used.

Results of the SW pressure amplitude inside the bulk of the iron target obtained by using of the above dissimilar equations of state [14 - 16] are presented in Fig. 4.

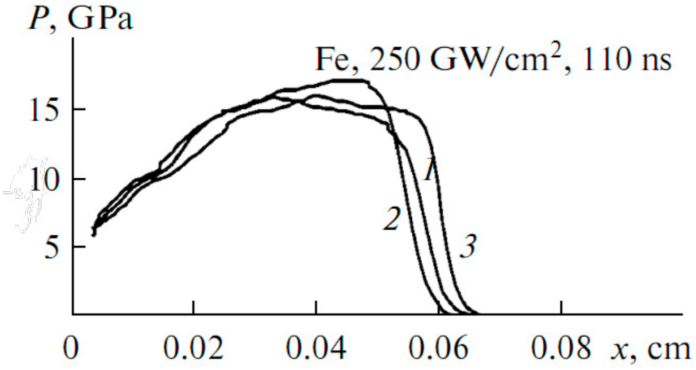


Fig. 4. The dependence of the SW pressure at the pulsed discharge in a DPF on the distance at its passage inside the bulk of an iron target: 1 – the equation of state based on the shock (Hugoniot) adiabat [15], 2 – the Mie-Grüneisen formula [14], and 3 – the Murnaghan relationship [14]

In this picture the pressure-distance curve is presented for the SW generated inside the bulk of material at the action upon its surface (x = 0) of the deuterons stream. At these calculations the following parameters were used:

mean deuterons energy E_i = 100 keV, their projective path d = 1 μm [14], power flux density of the ion stream q = 250 GW/cm^2, pulse duration of the ion stream τ = 100 ns. Results presented in the picture relate to the moment of time t = 110 ns counted from the beginning of the action of the ion stream. Pulse shape of the stream in all calculations presented it this work is described as a sinusoid $q(t) = q_0\sin(\pi t/\tau)$ with $q(t) = 0$ at $t < 0$ and $t > \tau$.

The curve 1 is calculated with use of the equation of state in cold matter in form of the shock adiabat [15]:

$$P = \frac{A^2\rho(\rho/\rho_0 - 1)}{(B-1)^2[B/(B-1) - \rho/\rho_0]^2} \tag{1}$$

where ρ and ρ_0 are specific density of material in the state of its compression by a SW and in normal state correspondingly. Coefficients A and B connecting a speed velocity D of the SW front with the mass velocity u of the matter behind the front by the relationship $D = A+Bu$, have been taken from the work [16]

Curves 2 and 3 are calculated with the use of the data of the book [14] according to formulas Mie- Grüneisen (2) and Murnadhan (3):

$$P = a\left(\frac{\rho}{\rho_0}\right)^{2/3}\exp\left[b\left(1-\left(\frac{\rho_0}{\rho}\right)^{1/3}\right)\right] - c\left(\frac{\rho}{\rho_0}\right)^{m/3} + 3\Gamma\frac{\rho}{\mu}RT \tag{2}$$

$$P = \frac{K}{K'}\left[\left(\frac{\rho}{\rho_0}\right)^{K'} - 1\right] \tag{3}$$

where $a, b, c, m, \Gamma, K, K'$ – table's coefficients, μ – molar mass, R – gas constant.

From the curves (Fig. 4) one may see that the SW pressure amplitudes and velocities of the fronts differ not more than by 15%. So the further calculations of the SW pressure were provided with the use of the equation of state in the form of the shock adiabat (1). It is determined by two reasons. First, in contrast to the formulas (2) and (3) the equation (1) is not an empirical one, but it is deduced from the laws of conservation of mass and momentum at the SW front. Second, in the work [16] there is a vast amount of the materials on the dependences of the SW front velocity on the mass speed u for various materials including iron. Besides, the Murnaghan formula does not take into consideration the thermal component of pressure, and it may be used at the pressures not more than 50 GPa when the thermal component does not exceed 20%.

From the other hand, an estimation of the mean value of the pressure amplitude is possible to obtain from the pressure of the near-wall plasma coming from the following considerations. At the power flux densities of the ion stream examined in this work, a very fast heating of the surface layer of the target up to the temperature higher than the critical one to the depth equal approximately to the ion range in the material takes place. Later an "explosive-like" evaporation of this layer occurs with the creation of the secondary plasma (SP) of the target's material in front of the irradiated surface. It is accomplished by the SP spread under the action of its own pressure. Coupling between the characteristic velocity of the SP spread V and the mean pressure of it in the one-dimensional approximation may be obtained from the second law of Newton: $d\rho_0 V/\tau \sim P$. Besides, as an analysis is shown, energy of the irradiating ion stream is spent approximately in the equal portions into kinetic energy of the flying away of the SP and to the processes connected with ionization, luminescence and thermoconductivity of the irradiated material. By another words, the equation $q_0\tau \sim d\rho_0 V^2$ is roughly true. From these two relationships one may obtain an estimation of the pressure: $P \sim (q_0\rho_0 d/\tau)^{1/2}$. Assumed, that the functional dependence of the pressure in the SW on the main beam parameters and on the target is the same and making a choice in favor of the numerical coefficient 1 one may obtain an analytical estimation of the SW amplitude from the consideration of the best matching of it with the results of the numerical calculations:

$$P_A \approx \sqrt{\frac{q_0 \rho_0 d}{\tau}} \tag{4}$$

In the work [17] the experiment made in the PF-1000U facility has shown a pressure in the SW passing through the stainless steel plate $P \approx 16$ GPa. Calculations presented in Fig. 4 conform to the experimental conditions. The analytical estimation (4) gives $P_A \approx 14$ GPa. It is also well fitted to the experiment.

4.2. Modelling of the interaction of the powerful laser beam with a solid target. Comparison with the previous case.

The method of the numerical modelling of the SW generation in a solid target by means of laser irradiation is the same as in the DPF case. The main dissimilarity is connected with the absorption mechanism of laser radiation.

Because in the presented experiments laser radiation with the wave-length of $\lambda = 1.06$ µm was used, and the laser beams has a medium power flux density $q \sim 10^{14}$ -10^{16} W/m^2, only the inverse bremsstrahlung absorptions was taken into account here as in the work [18]. Coefficient of the inverse bremsstrahlung absorptions is:

$$k = \frac{n_e \nu_{ei}}{n_{\hat{e}\eth} c \left(1 - \frac{n_e}{n_{\hat{e}\eth}}\right)^{1/2}} \tag{5}$$

where c – speed of light, plasma critical density $n_{cr} = \cdot 10^{21}/\lambda^2$ cm^{-3}, rate of the electron-ion collisions: $\nu_{ei} = 3 \cdot 10^{-6} \frac{n_e Z \Lambda}{T^{3/2}}$, $\Lambda \sim 5$-10 – Coulomb logarithm, T – plasma temperature in eV.

Numerical modelling was related to the SW generation in a flat geometry for the targets made of Al and W. Laser beams has characteristics as those for the streams of fast ions in a DPF: $\tau = 100$ ns, $q = 10^{14}$ and 10^{15} W/m^2.

Below one may see the pressure distributions in cold matter at the moment of the termination of the ion and laser beams (Fig. 5). All the upper curves are related to the DPF case whereas the lower curves – to the laser.

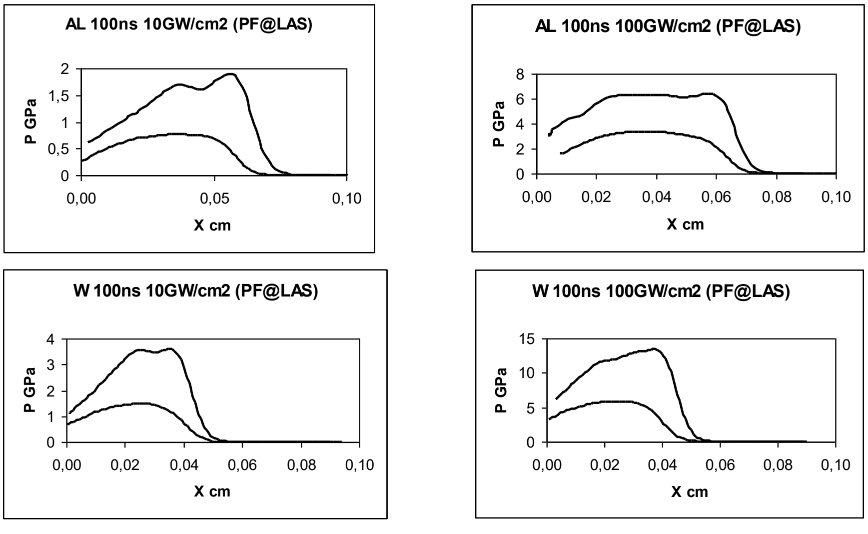


Fig. 5. The dependence of the SW pressure at the pulsed discharge in a DPF at the fast ion streams action and at the laser beam irradiation of the targets on the distance at its passage inside the bulk of an aluminum and tungsten targets

The most important result is the following: at the about the same energetic and power flux density characteristics DPF fast ion streams form SWs with amplitudes of about two time higher in comparison with the laser case. Besides, the SW front formation in a DPF is created faster compared to the laser irradiation event. It is explained by the fact that laser light does not penetrate into plasma with its density higher than the critical one. For the Nd-glass laser n_{cr} =·10^{21} sm^{-3}, what is two orders of magnitude lower than the atoms concentration is solid state. That is why density and consequently pressure in laser produced plasma are sufficiently lower than in the case of plasma created by the streams of fast ions generated in a DPF. Main results of numerical calculations are presented in a Table 1.

Table 1. Results of numerical calculations for the Al and W targets

Target	Device	q [GW/m^2]	τ [ns]	T [eV]	P [GPa]	P_A [GPa]
Al	PF	10^{14}	100	13	1,9	2,0
Al	LAS	10^{14}	100	50	0,8	_
Al	PF	10^{15}	100	27	6,3	6,4
Al	LAS	10^{15}	100	180	3,4	_
W	PF	10^{15}	100	14	3,5	4,4
W	LAS	10^{14}	100	60	1,5	_
W	PF	10^{15}	100	28	13	14
W	LAS	10^{15}	100	200	5,9	_

Table 1 contains the main results. Temperature values T presented in the table are related to the moments of the beams intensity maxima whereas the SW pressure amplitudes P are corresponded to the final moments of the beams action. It should be noted that temperatures of laser produced plasma are 4-6 times higher compared to the ion stream cases. Nevertheless, due to much higher differences in plasma densities the SW amplitudes generated in a DPF are about 2 times higher compared with the SW produced by laser irradiation. The SW amplitudes P_A calculated by using the formula (4) are in a good agreement with the results of the numerical modelling.

5. Conclusions

1. Experiments provided with fast ion streams in a DPF and with a Nd-glass laser operating in a Q-spoiled mode with power flux densities of about 10^{15}-10^{16} W/m^2 have shown in the cross sections of the targets of Mo and W the specific damages as the cracks oriented in parallel to the surface.
2. These cracks are observed in the regions of the materials bulk that is 2 order of magnitudes deeper compared with the ion range and much deeper than the depth of the laser light absorption.
3. These facts are testified to the formation of Shock Waves (SW) in material by the above-mentioned powerful beams.
4. Numerical modelling of the SW formation under the action of the above-mentioned beams has been provided.
5. By these calculations it is shown that in the radiation material experiments with the equal aforesaid power flux densities of the beams the DPF radiation produce SW with amplitudes about 2 times higher compared with the laser case. Besides, the SW front formation occurs faster in a DPF compared with the laser irradiation.
6. A simple analytical formula for calculations of the amplitudes of shock waves in radiation material science experiments provided with Dense Plasma Focus devices are advanced.

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