Study on Thermodynamic Process Produced by Intense Pulsed Electron Beams[1]

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Abstract – With high power density electron beams (HPDEB) generated by multi-gap pseudospark discharge chamber, we have studied on surface modification of various kinds of metal targets. In this paper, the thermodynamic processes and its effects created by such HPDEB have been studied theoretically and experimentally. The interactions of electron beam and metal materials were theoretical considered and discussed on the basis of simple calculated with one dimensional thermal transfer equation. It showed that the cooling rate of metal surface accessed to $1.2 \cdot 10^{12}$ K/s.

By analyzing of both experimental data and computer simulations, behaviours of thermal shock for aluminum and 45# steel targets under the irradiation of HPDEB have been obtained. For aluminum target, single thermal shock peak is supposed to be generated by impact thermal stress and the recoil compress of melted clusters leaving the irradiated surface. The sample surface was melted and situated in hydrodynamics state. For 45# steel target, double waveform and twin-peak thermal shock were caught. Double waveform is supposed to be the coexistence of elastic wave (the former) and plastic wave (the later). The twin-peak is supposed to be caused by phase transformation. Experimental results are well correspondent with the computer simulation.

1. Introduction

High power density electron beams, generated by multi-gap pseudospark discharge chamber, have been used for bombardments of various kinds of steel targets such as 45#, 65Mn, T8, 9Cr18, GCr15 etc., the applications of high power density electron beam for modification of metal surface were studied in our previous works. The analysis of thermodynamics effects under the irradiation of intense pulsed electron beams shows that the most of energy deposited on material surface in a very short time (pulse duration ~20 ns) will cause a nonequilibrium process including fast heating, melting, phase transformation, and high temperature gradient and so on in target surface region. Subsequently, target surface will cool down rapidly due to heat conducting. Such rapid melting and abruptly cooling could lead to a modification of surface microstructures from crystalline to amorphous. If the power density of pulsed beams is high enough, a series of thermodynamic nonequilibrium process such as vaporization and ablation will also appear.

It is necessary to analyze thermodynamic shock process theoretically and experimentally to realize thermo- dynamic interaction between such HPDEB and intense pulsed electron beam (IPEB) and target material. In this paper, behaviours of shocks and its effects created by the IPEB bombardment have been studied by using our shock detecting system. Then experimental results are discussed and compared with our numeric analysis with our computing program STEIPIB [1].

2. Experiment

1) Intense pulsed particle beam sources:

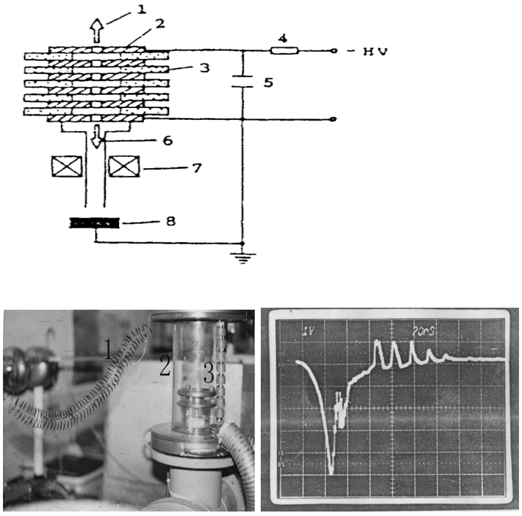

Fig. 1. a) Schematic diagram of the multi-gap chamber for the production of pulsed electron and ion beams: (1) ion beam, (2) metallic plates, (3) insulating plates, (4) charging resistor, (5) external capacitor, (6) electron beam, (7) wideband current transformer, (8) target. b) Device and typical electron current profile: (1) high voltage, (2) vacuum chamber, (3) capacitors

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In our experiments, we studied the measurements of shocks induced by both IPIB and IPEB bombardments. To get IPEB, a pseudospark discharge device was used. The key part of the device is a multi-gap pseudospark discharge chamber (MPC) [2]. The structure of MPC and a typical electron current profile are shown in Fig. 1. A typical duration of such IPEB is 20 ns.

2) Detecting System:

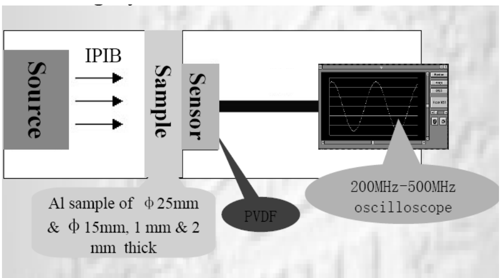


Fig. 2. Schematic diagram of PVDF detecting system

Our detecting system is composed of a sample shelf, piezoelectric sensor, amplifier (if necessary), oscillo- scope and cables (shown in Fig. 3). The key part of piezoelectric probe is a 100 m polyvinylidene fluoride (PVDF) film. Electric charges delivered on both electrodes were transformed to voltage signal via two 50 ohm resistors (Fig. 4). Two voltage signals were then coupled to an oscilloscope respectively. Wave profiles were caught and record by oscilloscopes of model TDS2024 (200MHz, 2Gs) and TDS3052B (500MHz, 5Gs).

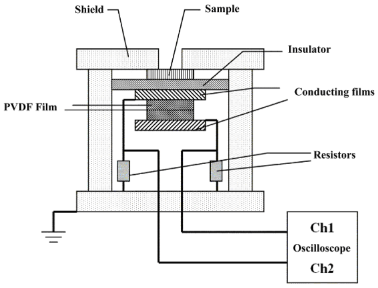
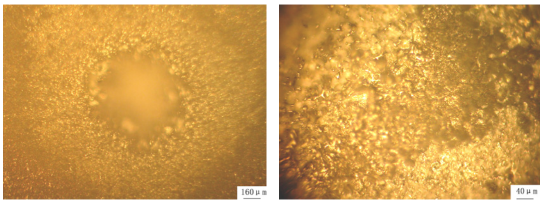


Fig. 4. Schematic diagram of PVDF detecting system

3. Results and Discussions

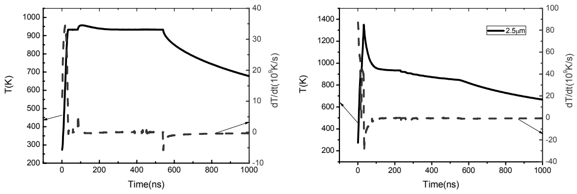
Crater produced by the irradiation of IPEB on the Al surface is showed in Fig. 5. Pictures were taken by XJB-1 microscope. The size of crater was 1 mm in diameter and 0.4 mm in depth as shown in Fig. 5. Melting state and spatter of melted drops were observed in Fig. 5, *b* as well.

With our STEIPIB codes, we calculated surface temperature of Al irradiated by IPEB with the same parameter. Calculating results were shown in Fig. 6. It showed that increasing rate of temperature accessed $2.76\cdot10^{10}$ K/s on the surface and $8.7\cdot10^{10}$ K/s at the depth of 2.5 μm. While the temperature on Al surface reached melting point at 32.5 ns, the temperature at the depth of 2.5 μm accessed to its maximum points of 1350 K. Such calculating results manifested that melting process began at one depth and the surface layer could keep liquid state for relatively long period and cool rate still kept $4.64\cdot10^{9}$ K/s at 541ns.



(a) crater (b) center of the crater

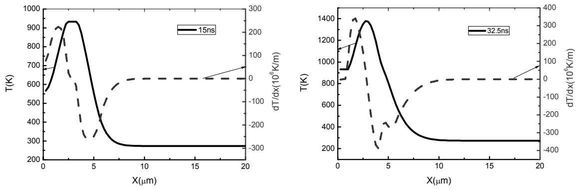
Fig. 5. Crater on Al surface produced by 25keV IPEB



(a) 表面 (b) 距表面２.５μｍ

Fig. 6. Temperature and its rate on the surface of Al target irradiated by 25KeV 2KA/cm^2 25ns IPEB

The gradients of temperature at the time of 15ns and 32.5 ns from beginning of IPEB irradiation with the same parameter were calculated and shown in Fig. 7. It showed that the gradient got the maximum value at the depth of 1.5 μm when temperature access to melting point at 2.5 μm. And the hottest region still kept melting state (1377 K) while it reached melting point on the surface. It meant that the crater in the center was formed due to ablation of melting spray caused by the bombardment of IPEB.



(a) 15ns (b) 32.5ns

Fig. 7. Temperature and it gradient on Al surface layer at 15 ns and 32.5 ns from beginning of irradiation of 25KeV 2KA/cm^2 25ns IPEB

Temperature distribution on near Al surface irradiated by 25 KeV, 4500 A/cm^2 and 25 ns IPEB was calculated and shown in Fig. 8. Even bombarded by such intensive electron beam, there was no vaporizing process appeared in Al surface region. Melting process was start at a site beneath the surface.

On the other hand, such IPEB, which has the same parameter bombards on Al target, irradiated on 45# steel got a similar result.

In Fig. 10, *b*, 45# steel was irradiated by 25 KeV, IPEB whose pulse number was greater than 100. Pictures were also taken by XJB-1 microscope. It shows that there has been melting state appeared in irradiated region.

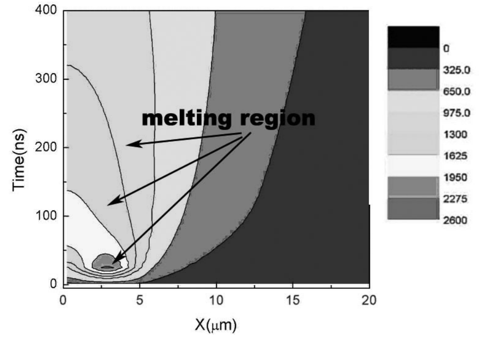
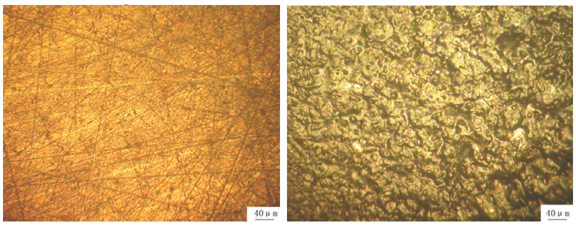


Fig. 8. Temperature distribution on Al surface irradiated by 4500 A/cm² IPEB



(a) blank sample (b) irradiated region

Fig. 9. Comparison of Surface of 45# steel irradiated by 25 keV IPEB with blank sample

A calculating result of temperature at the depth of 2.5 μm for 45# steel irradiated by 25 KeV, 3000 A/cm², 25 ns IPEB has been shown in fig. 10. The heating rate of 45# steel surface is so extremely high that it is $7.9 \cdot 10^{10}$ K/s at the time of 25 ns when surface temperature reaches to melting point (1808 K). Only lasting 1 ns, surface starts cooling at speed of $1.5 \cdot 10^{10}$ K/s. Such cooling rate keeps $1.0 \cdot 10^{9}$ K/s even at 200 ns later. It means that melting states are kept in a very short period and steel samples are in the state of elastoplastic liquid.

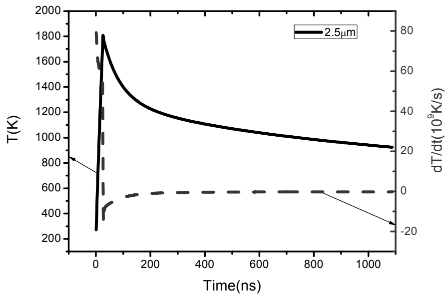


Fig. 10. Temperature and dT/dt 2.5 μm beneath the surface of 45# steel irradiated by 25KeV 2KA/cm² 25ns IPEB

Deep profiles of craters on the irradiated surface are actually due to the process of interaction between IPEB and target material which including three stage:

(a). Focusing of electron beam:

Beam size could deduce to 300 to 500 μm when it reached on the surface of target material [3].

(b). Slowdown and shrinking at the beginning of implantation:

At this stage, electron has high energy and low energy losing.

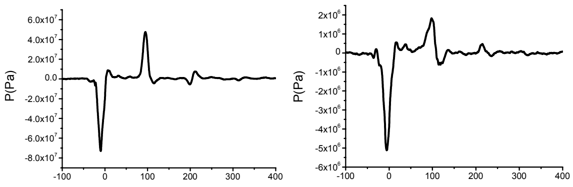
So the speed of electron decreases slowly and part of charge deposits as following [4].

$$\rho = \Delta t(J_i - J_{bs} - J_{se} - J_c). \qquad (1)$$

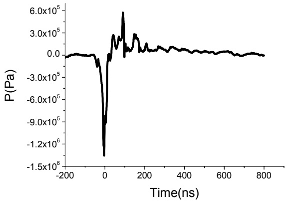
Where J_i is the current density of incident electron beam, J_{bs} is the current density of backscattering beam, J_{se} is the current density of secondary emission electrons, J_c is the current density of conductor and Δt is increasing factor of time. Because Δt is relative smaller and $J_{bs} \times J_{se} \times J_c$ relative bigger, thus ρ_{is} very small and only small part of charges are deposited. In addition, a plasma path with high conductance forms in the target due to ionization effect. Electron beam continue shrinking and is neutralizing.

(c). Fast deposition of beam energy and charges:

When beam energy decreases to 10^2 eV, energy losing increases and beam expands rapidly. Temperature of energy deposition region increases very fast, and melting materials are sprayed. This ablating spray leads to recoiling impulse effect and induces shock in the target material.



(a) 1mm (b) 2mm



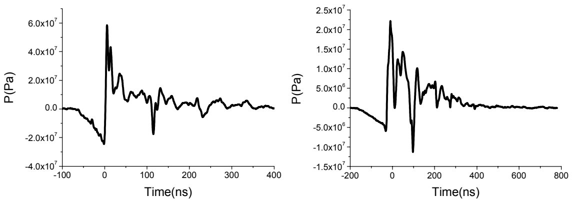
(c) 3mm

Fig. 11. Shocks induced by bombardment of 25 keV IPEB in Al target

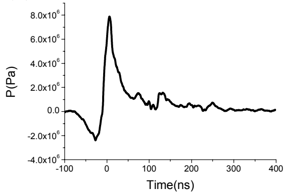
Fig. 11 and Fig. 12 show calibrated measuring results of shocks which were induced by 25 keV IPEB bombardment on Al and 45# steel of different thickness (1, 2 and 3 mm).

In Fig. 11, *a* and Fig.11, *b*, there were two waves detected in each Al sample, and the second was the reflecting one. Shock measurement results also told us that peak shock at the backside of Al sample was 0.0475 GPa. According to the correlation of field strength of Al with its temperature [5–7], peaks of shock in Al target were much higher than the field strength of Al and targets were in a hydrodynamic state. Thus there was only single peak of compressive shock.

Twin-peak structure and double waveform appeared in 45# steel sample, as shown in fig. 12. According to the correlation of field strength of 45# steel with its temperature [5–7] peaks of shock in 45# steel target were similar to field strength of 45# steel and steel targets were in an elastoplastic state. In such case, elastic wave (the former) and plastic wave (the later) appeared together. As the propagating distance increased, such twin-peak structure and double waveform disappeared. It may be due to the disappearance of plastic wave as strengthen of shock decreases during the wave propagation.



(a) 1mm (b)2mm



(c) 3mm

Fig. 12. Shocks induced by bombardment of 25 keV IPEB in 45# steel target

4. Conclusion

1) There are also high heating rates and cooling rates during the irradiation of IPEB on metal surface.
2) The craters on target surface irradiated by our IPEB could attribute to the ablation of melting spray caused by the bombardment of IPEB.
3) For aluminum target, single thermal shock peak is supposed to be generated by impact thermal stress and the recoil compress of melted clusters leaving the irradiated surface. The sample surface was melted and situated in hydrodynamics state.
4) For 45# steel target, double waveform and twin-peak thermal shock were caught. Double waveform is supposed to be the coexistence of elastic wave (the former) and plastic wave (the later). The twin-peak is supposed to be caused by phase transformation.

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