The Characteristics of Distribution of Craters on the Surface of Several Metal Irradiated by IPIB[†]

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The bombardment of intense pulsed ion beam has been shown leading many physical and chemical effects. As a flash heating source, it produced a fast heating and cooling process in the region near the surface of target. Besides the evidence of formation of amorphous layer and phase transformation, there were many craters of various kinds found on the surface of target.

In this paper, we studied the distributions of these craters according to the beam parameters such as ion energy (accelerating voltage), beam current density, pulse number, etc.. These beam parameters are 250 keV of ion energy, 72~200 A/cm² of beam current density, 60 ns of pulse duration and 2~24 of pulse number, respectively. The surface morphology was observed with SEM and the compositions were determined by EDS methods. Also statistical comparisons of crater distributions at different beam parameters were given in the paper. Through our experiments and analysis, we obtained that there are several kinds of craters appeared in our experiment. The size and number of crater varies according the beam parameters. The discussion about the reason of formation of those craters was also given in this paper. And the main factors to form craters on melted surface were the surface energy state distributions and eroded particles from ion sources.

Key Words : Intense Pulsed Ion Beam, Crater, Surface Roughness, Material Processing

1. Introduction

The pulsed energy deposition of Intense Pulsed Ion Beam (IPIB) can induce a fast heating-cooling process and leading many physical and chemical effects in the target surface. Proper utilizing these effects could enhance the surface service properties of materials, such as microhardness, corrosion resistance, wear resistance, surface roughness and so on. But the improvements of surface properties have been proved, by experimental and theoretical analysis^(1~3), to be tied up with the beam parameter, i.e. accelerating voltage, beam current density, pulse duration, pulse number, etc..

The characteristics of irradiation of IPIB are due to the ion beam energy deposition profile. Commonly, temperature on metal surface may reach the melting point with the beam current density ≥ 80 A/cm² and pulse duration ≥ 50 ns, and the melting and vaporizing of target metal under the irradiation of IPIB may affect the surface roughness, one of the surface service properties, obviously. In order to understand the formation of craters on the irradiated surface and influence of the beam parameter on the crater formation, we tried to study some characteristics on the melted surface, especially the craters.

2. Experiment

Samples in our experiments were pure aluminum,

Ni₃Al based alloy IC6, 45# steel and silicon crystall ; in which 45# steel was composed of Fe 98.63%, C 0.45%, Si 0.26% and Mn 0.65% and IC6 alloy consisted of Ni—(7.4~8.5)Al—(12~15)Mo—(<0.1)B % (wt). They were cut into round pieces with 10 mm in diameter and about 1~2 mm in depth. The irradiation beam was generated by the TEMP accelerators, which located at the Nuclear Physics Institute, Tomsk Polytechnic University, Russia and the Key Laboratory of Materials Modification by Laser, Ion and Electron Beams, Dalian University of Technology, China, respectively. The compositions of IPIB were 30% of H⁺ and 70% of Cⁿ⁺. The ion accelerating voltage was 250 kV, beam current densities were 72 A/cm² ~ 200 A/cm², and pulse duration is 60 ns. After the irradiation, some surface morphological characters of samples were observed with S-4200 SEM and some with KYKY 2800 SEM. The compositions of target surface were observed by X-ray Energy Dispersive Spectrometry (EDS). Observation results are shown below.

3. Experimental results

Fig. 1 gives the surface morphology of aluminum and Fig. 2 gives the other three samples that treated by IPIB. Our observations showed that the irradiated surfaces were full of craters and caves. All three types of craters classified depending on the crater shape⁽⁴⁾—craters with convex center and concave center, multi-rings craters and adjoining craters—were observed here. Round shaped craters appeared on the surface of all four kinds of samples(as Fig. 1 and

[†]This work was supported by the National Natural Science Foundation of China (No. 10175003 and No. 19975003)

Fig. 1 Al Surface irradiated by IPIB of 250 keV, 60 ns, 200 A/cm² (a) and 120 A/cm² (b).

Fig. 2 showed). Multi-ring craters belonged to large-scaled craters (diameter $\sim 50 \mu\text{m}$ or larger) and were observed on the surface of 45# steel, IC6 alloy and silicon chips, but they were not observed on the Al surface in our experiments. Instead, aluminum surfaces were destroyed severely while current density accessed 100 A/cm² or higher.

On the surface of silicon chips, the common situation was that the irradiated surfaces were full of striped cracks, some had flaked from the samples and left the structure of crystal main body uncovered. In the region that the surface hadn't flaked, we observed all three types of craters (see Fig. 2(a)).

The analysis results of the crater distribution on 45# steel and IC6 alloy presented in Table 1 and Fig. 3. For 45# steel, crater density increased via the irradiated beam current density. But the crater density decreased for IC6 alloy when current density exceeded 150 A/cm². Considering the craters formed on examined samples with the diameter $\geq 50 \mu\text{m}$, we couldn't figure out directly any correlated characteristic between large crater density and beam parameter.

Fig. 2 Craters formed on the surface of Si (beam current density : 120 A/cm²) (a), 45# steel (beam current density : 200 A/cm²), and IC6 alloy (beam current density : 100 A/cm²) (c).

Table 1 density of crater formed on 45# steel and IC6 alloy surfaces.

No.	Sample	Beam Parameter				Crater Numbers
		V (kV)	J (A/cm ²)	τ (ns)	Pulse numbers	Density (/cm ²)
1	45# steel	250	72	60	4	$2.98 \times 10^4 \pm 1.87 \times 10^4$
2	45# steel	250	120	60	3	$5.35 \times 10^4 \pm 2.73 \times 10^4$
3	45# steel	250	180	60	2	$6.74 \times 10^4 \pm 1.48 \times 10^4$
4	IC6 alloy	250	100	60	24	$2.78 \times 10^4 \pm 5.1 \times 10^3$
5	IC6 alloy	250	150	60	16	$2.67 \times 10^5 \pm 3.86 \times 10^4$
6	IC6 alloy	250	200	60	12	$4.25 \times 10^4 \pm 6.8 \times 10^3$

To explore the cause of crater formation, we analyzed surface chemical compositions with EDS method. Fig. 4 gave the EDS analyzing results in the center of a multi-rings crater formed on IC6 surface. Many elements other than the original Ni, Mo, Al had appeared in this region. Other EDS analyzing results also showed that some large scaled craters and multi-rings craters were polluted by structural material in the accelerator, for example the structural material of the cathode system (because of the appearance of Sn). For those small scaled craters and some other large

(a)

(b)

Fig. 3 Crater number of all kinds of craters(a) and of diameter $\geq 50 \mu\text{m}$ (b) formed on the surface of IC6 alloy.

scaled craters, the compositions were closed to the one of IC6 alloy. It means that these craters were induced by the melting or vaporizing process on target surface.

4. Discussion

For 45# steel, silicon crystal, IC6 alloy and aluminum, the melting points are 1809 K, 1685 K, 1588 K and 933 K, respectively. Our calculation had manifested that the surface temperatures of these four materials exceeded the melting point when it was bombarded by IPIB of 80 A/cm², 250 keV, 50 ns^(3,5),6). Fig. 5 exhibited the temperature on silicon crystal surface bombarded by IPIB of 80 A/cm², 250 keV, 60 ns. In the calculation, difference of melting point with different material density and environmental pressure was not considered. It should be lower than the one we used. Even though, it was still obvious that the surface of silicon had melted here. Our former calculation about 45# steel, also presented the melting process

Fig. 4 Composition of multi-ring crater formed on IC6 alloy obtain by EDS method.

Fig. 5 Temperature on the surface of silicon irradiated by IPIB of 250 keV, 80 A/cm², 60 ns.

with the same beam parameters⁵⁾. But there no melting process obtained by our calculation with the beam parameters similar to above but current density of 40 A/cm². In accordance, it was hardly to observe any craters on the surface irradiated by IPIB of 40 A/cm². So melting process is one of the necessary conditions to form craters.

There existed a characteristic current density for

each kind of materials. Irradiated at this current density, the solid surface had the highest total crater density. As Table 1 had showed, the characteristic current density for IC6 alloy was around 150 A/cm^2 . But for 45# steel, it rise to above 200 A/cm^2 . This may be explained as differences between the melting points caused different behavior of crater density, especially for those small scaled craters which were the main part of craters.

On the other hand, if the beam intensity was high enough, the surface of solids may deeply melt or ablate. At this case, craters formed at the early heating steps would be vanished. Photos of aluminum surface demonstrated such phenomena.

Furthermore, the distribution of atom physical and/or chemical state (energy state) on the solid surface was also a factor affecting the formation of craters. Because there were few defects on the surface of silicon crystal, the energy state was uniform. In accordance, number of craters formed on it was also lower than those formed on steel and IC6 alloy, which were mainly composed of polycrystal.

Through EDS analysis, we can make it clear that bombarding of particles to melt the surface or directly on the melted surface was another factor in the formation of craters. These particles came from the eroded structural material of the cathode system in ion sources. According to our observation, numbers of craters formed on the silicon surface irradiated by IPIB with two different current densities were similar. It means that the craters formed on silicon surface were primarily due to the bombarding particles.

5. Conclusion

In this study, three major conclusion were obtained as :

1. All three types of craters classified depending on the crater shape-craters with convex center and concave center, multi-rings craters and adjoining craters-were observed in our experiments.
2. For each material, there exists a characteristic current density that induced the highest crater density.
3. Formation of craters on irradiated solid surface is mainly due to the following :
 - (1) The melting vaporizing or ablating state on metal surface ;
 - (2) Defects distribution or surface atom physical and/or chemical state (energy state) distribution ;
 - (3) Bombarding of eroded particles from ion sources.

(Received December 27, 2002 ; Accepted August 27, 2003)

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