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# Elastic wave from fast heavy ion irradiation on solids

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**Abstract**

To study the time-dependent mechanical effects of fast heavy ion irradiations, we have irradiated various solids by a short-bunch beam of 95 MeV/u Ar ions and observed elastic waves generated in the bulk. The irradiated targets were square-shaped plates of poly-crystals of metals (Al and Cu), invar alloy, ceramic ($Al_2O_3$), fused silica ($SiO_2$) and single crystals of KC1 and LiF with a thickness of 10 mm. The beam was incident perpendicular to the surface and all ions were stopped in the target. Two piezo-electric ultrasonic sensors were attached to the surface of the target and detected the elastic waves. The elastic waveforms as well as the time structure and intensity of the beam bunch were recorded for each shot of a beam bunch. The sensor placed opposite to the beam spot recorded a clear waveform of the longitudinal wave across the material, except for the invar and fused silica targets. From its propagation time along with the sound velocity and the thickness of the target, the depth of the wave source was estimated. The result was compared with ion ranges calculated for these materials by TRIM code. 

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## 1. Introduction

The local deformation initiated by irradiation should accompany time-dependent stress and strain in the material, which propagate in the material as elastic waves and can be detected at the surface by sensors. For real-time observations of such dynamical effects of the irradiation, we have studied the heavy ion-induced elastic waves from various materials employing the acoustic emission (AE) method. AE method have originally been developed for characterization of micro-fractures in materials through the detection and analyses of elastic waves in ultrasonic frequencies up to MHz [1], and we expect to see with this method mechanical processes in the range of 10 ns or longer which is much slower than the relaxation time of the electronic excitations. Some results with 26 MeV/u Xe ions have been reported previously [2,3].

In this paper, we report the observation of elastic waves generated in bulk by irradiation of 95 MeV/u Ar ions on various solids. We take a special interest in the position of the wave source

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relative to the range of the ions, and the relation between the amplitude and the bulk characteristics of the material. We measured the propagation time of the elastic wave to determine the depth of the wave source, and compared the result with the range of the ions calculated by a TRIM code [4].

## 2. Experiment

The experiments were performed at RIKEN accelerator facility with a 95 MeV/u Ar beam which consisted of a single-bunch pulse with a width of 3 ns and an interval of about 60 ms. The beam preparation, monitoring and irradiation set-ups were similar to those for the previous experiments [2,3].

The following samples were irradiated: poly-crystalline metals (Al and Cu), single-crystalline alkali-halides (LiF and KCl) a poly-crystalline $Al_2O_3$, a fused silica ($SiO_2$), and an invar alloy. The samples were square-shaped plates with a common dimension of about 40 mm $\times$ 40 mm $\times$ 10 mm except for the Cu which was 35 mm $\times$ 35 mm $\times$ 10 mm. The beam spot size was about 4 mm $\times$ 4 mm and the beam was incident perpendicularly on the square-shaped surface (face plane). Two single-crystal KCl samples were used whose surface were $\{1\,0\,0\}$ and $\{1\,1\,1\}$. The velocities of the longitudinal and shear waves in the bulk were measured by a sing-around method.

Before the sample, the beam passed through two beam monitors with secondary-electron detectors: The first one was a fast monitor with a multi-channel plate (MCP) to pick up the timing and micro-structure of the beam bunch, and the second was a slow monitor to measure the intensity of the beam bunch.

The elastic wave was detected by piezoelectric (PZT) sensors (Fuji Ceramics, M304A) [5]. The sensor is a circular rod with diameter of 3 mm equipped with a head amplifier, and is sensitive to oscillation perpendicular to the surface. The highest sensitivity is about 115 dB at about 300 kHz. Two sensors were attached to a sample: one, referred hereafter as side sensor, was on a side plane, and the other, referred as back sensor, at the center of the back plane opposite to the face plane where the beam hit. The sensors were pressed on the surface by a spring at about 1 kgf with vacuum grease between them. The sample with the sensors was held on a frame at the end of a linear motion feedthrough. Moving the frame perpendicular to the beam direction, we changed the position of the beam spot on the sample. The signals from the two sensors along with those from the slow and fast monitors were recorded by a digital oscilloscope for an individual shot of a beam-bunch.

In this experiment, we intended to deduce the position of the elastic wave source from its propagation time. Therefore it was important to determine the absolute time relation between the arrival of the beam-bunch and the detection of the elastic waves. The timing of the beam bunch was detected by the MCP of the fast monitor and the signal was directly transmitted without any electronic processing to the oscilloscope. On the other hand, the elastic wave signal detected by the piezoelectric sensor was amplified by a head amplifier in the sensor, therefore the delay in the amplifier should be corrected. We determined the instrumental delay by irradiation of a pulse YAG laser (width of about 7 ns) directly on the sensor. We also corrected for the time lag due to the difference of the signal-cable lengths and the time-of-flight of the ions from the fast monitor to the sample surface. In Figs. 1 and 2 where the elastic waveforms are displayed, the zero of time is the arrival time of the ion on the sample thus determined.

## 3. Results

Figs. 1(a) and (b) show elastic waveforms observed by the side sensor and back sensor, respectively on the Al sample for different beam-spot positions. A typical beam-bunch signal from the fast monitor is also shown. Relative to the waveform at the top denoted as (A), the sample was moved perpendicular to the beam towards the side sensor by (B) 3 mm, (C) 6 mm, (D) 9 mm and (E) 15 mm. Therefore the side sensor was closest to the beam spot at the position (E). The delay time at the side sensor, shown in Fig. 1(a), decreases from (A) to (E) whereas the waveform is similar for all the positions. On the other hand, the delay

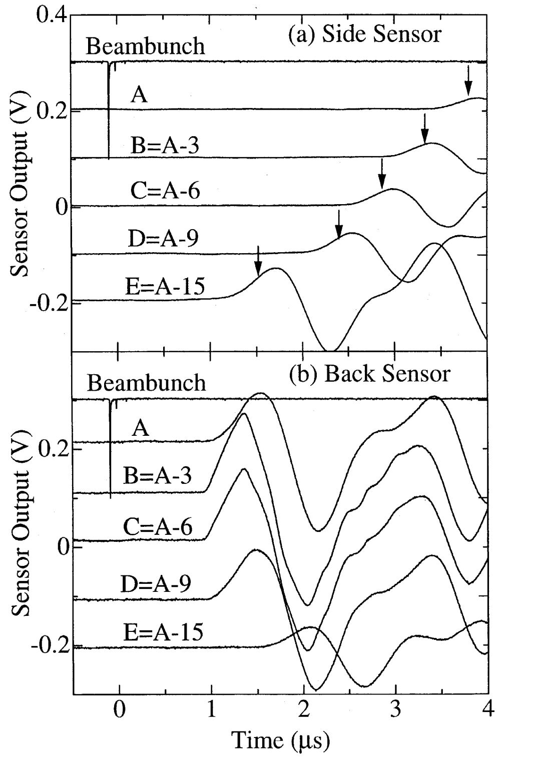


Fig. 1. Elastic waveforms observed at the side sensor (a) and back sensor (b) on Al sample along with the beam-bunch signal by the fast monitor. A–E denote the waveforms for different beam-spot positions. Arrows in (a) show the expected arrival time of the longitudinal wave to the side sensor.

time at the back sensor in Fig. 1(b) is shortest and waveform is sharpest at positions (B) and (C). Since the back-sensor waveforms at (B) and (C) are very similar, we conclude that the back sensor was almost in the middle of the beam axes for (B) and (C). We have estimated arrival time of a wave to the side sensor, assuming that the wave is longitudinal and the back sensor was at the center of the surface, which means the distance between the beam axis and the sensor at (A) was 24.5 mm. The results are shown by arrows in Fig. 1(a). Considering the beam-spot size of about 4 mm, the estimation is in good agreement with the observed arrival time. Therefore we can conclude that the observed elastic wave is the longitudinal wave with similar waveform in all propagation directions, except for the very forward one.

Figs. 2(a) and (b) show the waveforms measured by the back sensor for various samples. The position of the beam spot corresponds to position (B) in Fig. 1 where the center of the sensor was about 1.5 mm from the beam center. This distance was smaller than the diameter of the sensor and the beam-spot size, therefore the shortest distance from the beam spot to the sensor was equal to the sample thickness. Since the sensor can detect the oscillations perpendicular to the surface and is positioned nearly opposite to the beam spot, it can

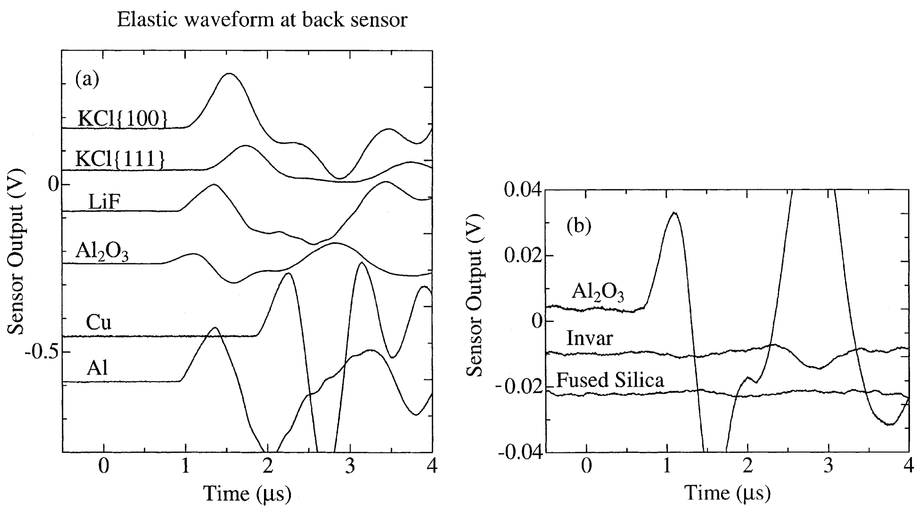


Fig. 2. Elastic waveforms captured by a sensor opposite to the beam spot. The waveforms are normalized to the beam-bunch intensity. The ordinate is expanded by a factor of 10 in (b).

detect only the longitudinal wave (compression wave) which is the fastest among the elastic waves.

The waveform is averaged over 40–50 shots to reduce the noise, and normalized to the slow monitor output so that they correspond to a same number (about $9 \times 10^3$) of ions.

Two of the materials, invar and fused silica, yield much lower amplitudes than others, as shown in Fig. 2(b). A common feature of the two materials is very low thermal expansion rates. It indicates that the process to generate the longitudinal wave (compression wave) is influenced by the thermal expansion of the material. However, for other materials where obvious elastic waves were observed, no direct scaling has been obtained between the amplitude and combinations of bulk thermal parameters of the material like thermal expansion rate and heat capacity. The results for invar and fused silica are not included in the following discussions.

There is a certain delay between the irradiation and the onset of the elastic wave. The delay corresponds to the propagation of elastic wave in the material to the sensor, and it depends not only on the sample material but also on the orientation of the crystal, as shown for the single crystals of KCl.

Multiplying the delay time by the velocity of the longitudinal wave, and subtracting it from the sample thickness, we obtain the depth of the wave source from the beam spot. The result is compared with the range calculated by the TRIM code in Table 1. The depths of the wave source are in accord with, but a little smaller than, the calculated ranges: The difference is 3–10%. In the case of KCl, there is no difference between the different crystal orientations.

The shape of the wave just after the onset reflects the characteristics of the mechanical stress by the irradiation. Both the back and side sensors detected the longitudinal wave with a positive output voltage at the onset. Since a positive output corresponds to an outward displacement of the surfaces, this result means that the stress at the source is compressive and propagates to all the directions. The width and rise time of the first peak of the waveform is also dependent on the material. For example, the peak for KCl is broader than that for $Al_2O_3$. The peak width is roughly in the same order as the ion range divided by the longitudinal wave velocity, or the elastic wave propagation time over the ion range. The rise time, time from the onset to the maximum, is 400–600 ns which is much longer than those previously obtained with 26 MeV/u Xe ions (about 70 ns), where the range was much shorter than the present case.

## 4. Conclusions

To study the transient mechanical stress and strain by fast heavy ions, we have irradiated different materials by a short pulsed ion beam, and observed with an AE method clear longitudinal wave signals from materials except for fused silica and invar alloy. Both the materials yielding very low amplitudes have small thermal expansion rates. For other materials, the observed waveforms have common feature: the wave arrives with the longitudinal wave velocity and the observed surface displacement at the onset is outward both at the side and back of the sample. It indicates that the wave is a compression wave which propagates from the source to all directions. These facts imply that the stress-generating process is closely related to thermal expansion by the deposited kinetic energy. However we cannot find a simple relation

Table 1
The experimental depth of the elastic-wave source from the irradiated surface is compared with the ion range calculated by the TRIM code

| | Al | Cu | $Al_2O_3$ | LiF{1 0 0} | KCl{1 0 0} | KCl{1 1 1} |
|---|---|---|---|---|---|---|
| Experimental | 4.10 | 1.41 | 2.53 | 3.98 | 5.65 | 5.68 |
| TRIM | 4.24 | 1.53 | 2.82 | 4.14 | 5.85 | 5.85 |

Values are in mm.

between the observed amplitude and the bulk characteristics of the materials like thermal expansion rates and heat capacities.

The depth of the wave source is estimated with the time delay of the onset of the wave observed opposite to the irradiation. The result is found to be in fair agreement with, but systematically smaller than, the calculation of the TRIM code, regardless of the kind of the material. It indicates that the code offers reasonable results of the stopping power for the 95 MeV/u Ar ions, and the stopping processes assumed in the calculation are valid. It also indicates that the source of the elastic wave closely matches the range of the ions.

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