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Wear diagnostics of industrial material using RI beams of ^{7}Be and ^{22}Na

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ABSTRACT

As a possible example of radioactive ion (RI) beams for industrial application, intense beams of ^{7}Be and ^{22}Na used for wear diagnostics of mechanical parts is considered. For wear diagnostics, radioactive nuclei which have appropriate long life-time such as from several weeks to a few years are applicable. As those nuclei are located near the stable line, an in-flight RI beam separator can provide intense RI beams with enough high energy for implantation in atmosphere. Beam studies were performed to evaluate the intensity, uniformity, and depth profile of the implanted RI. We could achieve peak activity of 1.3 and 0.08 (kBq/μm)/(1 pμA × 1 h irradiation) at 13 and 50 μm peak depth with 20 and 150 μm maximum depth from the surface of an aluminum sample for ^{7}Be and ^{22}Na, respectively.

1. Introduction

Industrial cooperation team in RIKEN Nishina Center (RNC) is promoting applications of high-energy heavy ions and radioactive ion (RI) beams for non-academic users including private companies in Japan. As a possible industrial application of RI beam, we are considering to use it for wear diagnostics of mechanical parts.

The evaluation of lifetime of the machine parts is important for effective maintenance and prevention of sudden failure of the machine systems. One of the factors that determines the lifetime of machine parts in motion is wear. A method called Thin Layer Activation (TLA) is used to measure the wear of machine parts utilizing radioisotopes as tracers. The near surface of the parts is activated and its wear-loss is evaluated by the decrease of the measured radioactivity. Continuous measurement of γ-ray from outside of the machine enables real-time diagnostics of wear in running machines. It does not need to disassemble and to clean the parts for each wear analysis, so that it enables a series of on-line tests of the machine system changing run conditions at one time. Thus, the TLA method is useful for wear diagnostics saving time and cost. Some application of this TLA method for automobile industry is reported in Ref. [1]. This method needs radioactive nuclides with sufficiently long lifetime. It should be the same order of the wear-loss measurement time, such as from several weeks to a few years. In addition, the activation area should be concentrated at the near surface of a wear sample within a few 10–100 μm.

In conventional TLA methods, the wear-loss sample is activated through nuclear reactions by a light-ion-beam irradiation. This "direct-beam activation" method is applicable for metals and alloys with elements that can be efficiently activated by ion-induced reactions, such as ^{56}Fe(p,n) ^{56}Co ($T_{1/2}$ = 78.8 day) and ^{65}Cu(p,n) ^{65}Zn ($T_{1/2}$ = 244.1 day) reactions. With this method, sometimes, unnecessary contaminant activities that interfere with the precise measurement are produced. The materials should be resistant to strong heat flux and radiation damage during the irradiation process, thus this method is difficult to apply to organic materials.

Nowadays, various kinds of new materials like ceramics and plastics are used in machine parts. Another method called "indirect activation" method has been proposed in which radioisotopes produced outside of the sample are implanted. Using proper nuclear reactions, the ^{7}Be recoiled-out from a reaction target was implanted to a sample placed close to the target [2–4]. In this method, a scattered primary beams and other nuclides are also implanted in the sample. As another example, ^{7}Be and ^{22}Na produced at a remote facility was re-accelerated and implanted into a sample [5]. It was necessary to handle RI with a high activity at the ion source under strict safety regulations.

An alternative possibility is to produce the RI beam using an in-flight type RI-beam separator. Recent development of a high-intensity heavy-ion accelerator permits production of intense RI beams. As the desired radioactive nuclei, which have lifetime from several

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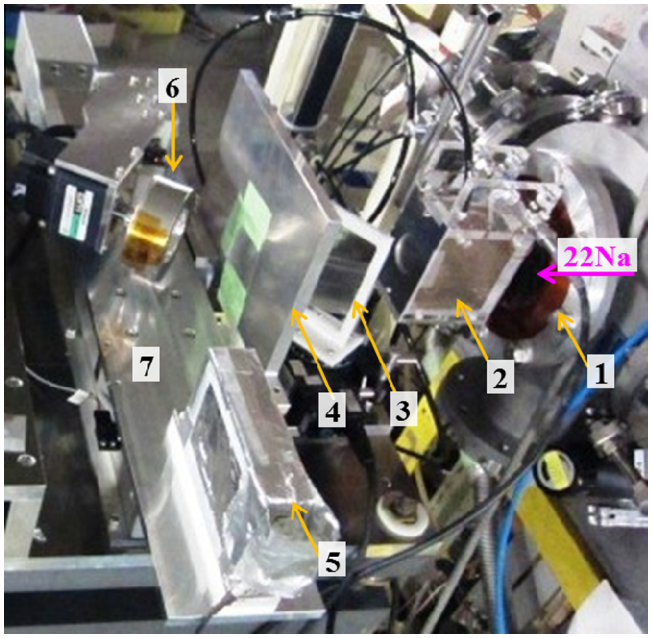

Fig. 1. Implantation setup for ^{22}Na beam. (1) Kapton foil window, (2) ion chamber, (3) variable-energy degrader, (4) beam collimator plate with a fixed-thickness degrader, (5) SSD energy detector, (6) irradiation sample of a machine-part, and (7) slide table.

weeks to a few years, are located near the stable line, the in-flight separator can provide intense RI beams with enough high energy. Using the high-energy RI beams, in addition, it enables to implant in atmosphere and to control the depth profile easily. In order to check the feasibility of this method, beam studies were performed to establish the procedure for implantation and to evaluate the intensity, uniformity, and depth profile of the implanted RI.

2. Available RI beams for wear diagnostics at RIKEN

Two beam studies were performed with the collaboration of S.H.I. Examination & Inspection Ltd. [6]. First one was for high-energy ^{22}Na ($T_{1/2}$ = 2.6 y) beam. The energy of the RI beam was high enough for implantation in samples placed in atmosphere. Second one was low-energy ^{7}Be ($T_{1/2}$ = 53 day) beam. This RI beam is low cost but the energy is too low for implantation in atmosphere.

2.1. ^{22}Na beam production

The ^{22}Na beam was produced from a stable ^{23}Na primary beam at projectile fragment separator (RIPS) [7]. A beam of $^{23}Na^{11+}$ was accelerated by a variable-frequency heavy-ion linac (RILAC) and a K540-MeV ring cyclotron (RRC) up to 63 MeV/A with intensity 1.0 particle-μA (pμA) in maximum and was led to the RIPS, where it passed through a water-cooled 1.5 mm–thick beryllium target. The radioactive ^{22}Na produced via fragmentation reaction of the primary ^{23}Na beam was separated with a dipole magnet and with an achromatic-degrader made of 1.2 mm-thick aluminum at F1 momentum-dispersive focal plane (F1). The $^{22}Na^{11+}$ beam in vacuum had energy of 26.6 MeV/A and size of σ = 13 mm in radius with the momentum slit of ±1.5% at F1. There was no contaminant nuclide. Fig. 1 shows the implantation setup in atmosphere. The RI beam was extracted from vacuum to atmosphere through a vacuum-separation foil of 75 μm-thick Kapton. Beam current was monitored by an ion chamber filled with He gas. The beam energy was adjusted by degrader foils made of aluminum. A fixed thickness degrader, 200 μm thick, was attached on a beam-collimator Al-plate with a diameter of 16 mm. A variable-energy degrader was a plate of 200 μm thick tilted relative to the beam axis, and its angle was programmable. The energy distribution of the RI ions was monitored with a solid-state detector (SSD), and the angle of the degrader was programmed to optimize the depth profile. It was set on the beam path at 53° (corresponding to 250.4 μm thickness) and 90°, alternatively, relative to the beam axis with time fraction of 3:1.

The three-dimensional distribution of implanted RI was evaluated with a foil stack consisted of 60 sheets of 6 μm thick Al foils. The activity distribution on each of the foils was taken by an imaging plate (I.P.) to visualize the two-dimensional beam-spot profile at different depths (Fig. 2). The I.P. used was a photostimulated luminescence film supplied by GE Health Care Ltd. (BAS IP SR: Super Resolution type). The distribution was found to be somewhat uneven. When we irradiate a machine-part, the sample was continuously rotated in the beam spot during implantation to average the distribution. The intensity of γ-ray (E_γ = 1275 keV, Branching 99.9%) at each layer of the foils was measured with a Ge γ-ray detector. Fig. 3 shows the result of the activity distribution of each foil as a function of the depth of the layers. In this figure, the ^{22}Na activation rate of (kBq/μm) is normalized by the dose of ^{23}Na primary beam (1 pμA × 1 h irradiation). *X*-error bars indicate the thickness of each foil, and *Y*-error bars indicate a statistical error of this measurement. From this result, we could achieve peak activity of 0.08 kBq/μm at 50 μm peak depth with 150 μm maximum depth from the surface for aluminum material. The machine-part was irradiated during about 26 h of this beam time with the primary ^{23}Na beam intensity of 1 pμA, approximately. About 172 kBq of ^{22}Na was found to be implanted and the intensity of the ^{22}Na beam was estimated to be 1.5 × 10^8/s.

2.2. ^{7}Be beam production

The ^{7}Be beam was produced via p(^{7}Li,^{7}Be)n reaction at the CNS RI beam separator (CRIB). A primary beam of $^{7}Li^{2+}$ was accelerated by a K70-MeV AVF cyclotron up to 5.7 MeV/A with intensity of

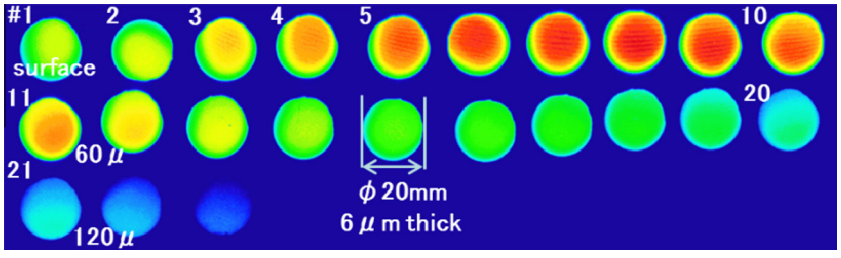

Fig. 2. Three-dimensional distribution of implanted ^{22}Na activity. Each of the irradiated foil was disassembled and measure by an imaging plate (BAS IP-SR). Number shows the foil-number from the surface. The color indicate an activity profile in each Al-foil of 6 μm thick. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

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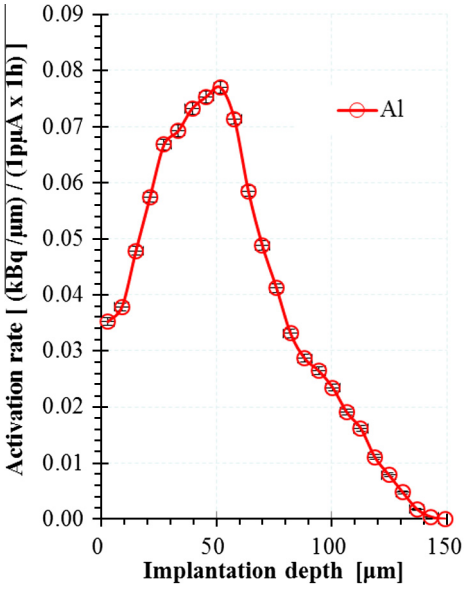

Fig. 3. Depth profile of implanted ^{22}Na activity. A stack of Al-foils in 6 μm thickness was measured by a Ge detector.

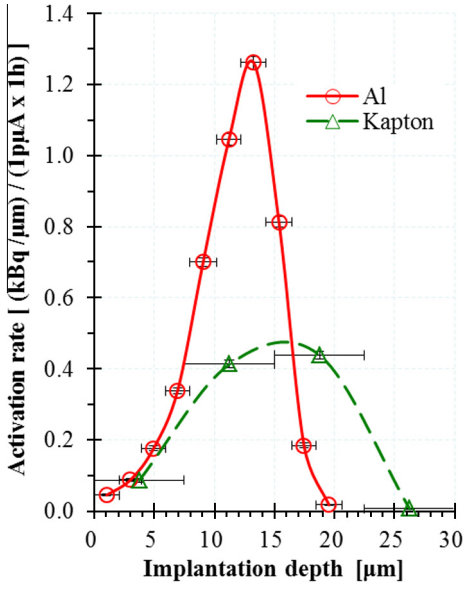

Fig. 5. Depth profile of implanted ^{7}Be activity measured by a Ge detector. A stack of Al-foils (2 μm-thick) and of Kapton-foils (7.5 μm-thick) are compared.

1.2 pμA in maximum and was focused on a cryogenic gas target [8] which was developed by the CNS group elaborately. The beam spot size was 1 mm in diameter. The target gas of H_2 with 760 Torr pressure was confined in a gas cell with beam entrance/exit windows of 2.5 μm-thick Havar foils. The gas was cooled by liquid N_2 vessel at 90 K and was circulated with a rate of 55 slm. The produced ^{7}Be beam was introduced to F2 focal plane without degrader foil at F1 momentum-dispersive focal plane. The $^{7}Be^{4+}$ beam in vacuum was 4.1 MeV/A in energy and size of σ = 6.1 mm in radius with the momentum slit of ±3.1% at F1. A contaminant nuclide of $^{7}Li^{3+}$ was observed with the fraction of 20%.

In order to enable ^{7}Be implantation under atmospheric pressure, a vacuum-separation foil of Kapton (50 μm thick) was assembled at the entrance of the F2 chamber and He gas of 1 atm filled the chamber. A compact implantation setup similar to Fig. 1 was adopted. The distance from the foil to the irradiation position was 14 cm. The ^{7}Li contaminant was stopped in the He gas, completely. Remained ^{7}Be beam was 100% in purity and its peak energy was 13.5 MeV with σ = 1.6 MeV in width. The intensity of ^{7}Be beam was 1.9×10^{8}/s obtained by the following γ-ray measurement, which reproduced a reported value in the Ref. [8]. In order to control the implantation depth to near surface, a variable-energy degrader was introduced. An 8 μm-thick aluminum foil was set on the beam path at 50° (corresponding to 10.4 μm thickness) and 90°, alternatively, relative to the beam axis with time fraction of 5:1.

To investigate an implantation-depth profile of ^{7}Be, two sets of thin-foil stack with 16 mm diameter were irradiated. The first one was a stack of 2 μm-thick aluminum foils and the second was a stack of 7.5 μm-thick Kapton foils. The irradiation time and total activity for both aluminum and Kapton stack was 11.2 h and 2.0 h and 103 kBq and 17 kBq, respectively. After irradiation, each stack was disassembled and the activity distribution on each of the foils was taken by an I.P. film (Fig. 4). The I.P. film used was BAS IP SR and MS: Multipurpose Standard type. Although the ^{7}Be emits a single γ-ray (E_γ = 478 keV, Branching 10.3%), the distribution could be measured clearly both I.P. of type-SR and MS. The intensity of γ-ray for each foil was measured by a Ge detector and the obtained implantation depth profiles are shown in Fig. 5. In this figure, the ^{7}Be activation rate of (kBq/μm) is normalized by the dose of ^{7}Li primary beam (1 pμA × 1 h irradiation). *X*-error bars indicate the thickness of each foil, and *Y*-error bars indicate a statistical error of this measurement. For the Al-foil stack, the activity distributes to the maximum depth of 20 μm and has a peak activity of 1.3 kBq/μm at 13 μm depth, and for the Kapton stack, the maximum depth is 27 μm and the peak activity of 0.5 kBq/μm is at 15 μm depth.

Comparing with the depth profile of ^{22}Na in the Al-foil stack (Fig. 3), whereas the total activity is almost same as 100 kBq for both case, the peak activity of ^{7}Be is much larger. This arises from the difference of the maximum depth of implanted RI beam. Although we can control the depth profile starting from the surface, but the maximum depth is determined by the width of momentum acceptance of the RI beam separator. During the energy degradation process before implantation, the momentum

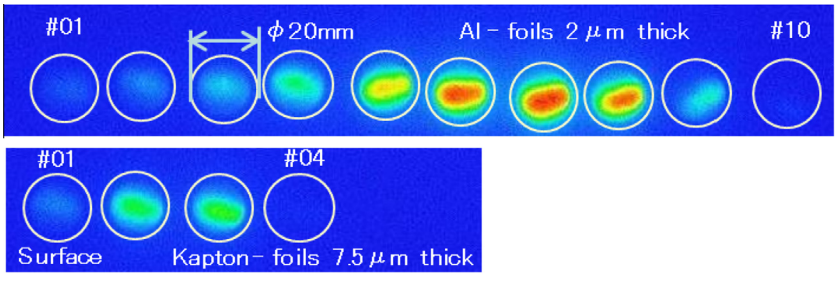

Fig. 4. Three-dimensional distribution of implanted ^{7}Be activity measured by an imaging plate (BAS IP MS). Upper and lower panel shows activity profile in each Al-foil of 2 μm thickness and Kapton-foil of 7.5 μm, respectively.

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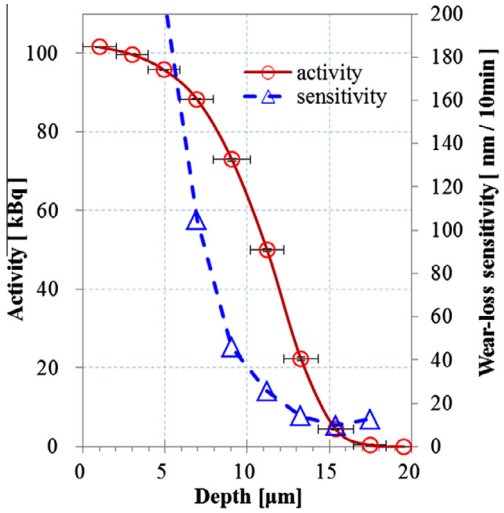

Fig. 6. The implanted ^{7}Be activity-depth profile of the Al-foil stack. Detectable wear-loss sensitivity under a certain condition (see text) is calculated.

width becomes larger especially for ^{22}Na beam that was produced and separated in higher energy. In this respect, low-energy RI beam production is convenient for achieving high-density activity at near surface.

Fig. 6 shows the activity of the Al-foil stack plotted as a function of the thickness of the layers removed from the beam-incident surface of the stack. This is for a simulation of a wear-loss analysis, where the decrease of the total γ-ray intensity of the sample is measured. As an example, we assume to measure it with a Ge detector of 1% efficiency for repeated 10-min counting period. Under this condition, the wear-loss sensitivity, which is defined as a one-standard-deviation change between successive counts due to the removal of the surface layer, is calculated and plotted in Fig. 6. We can achieve a best wear-loss sensitivity of 10 nm, approximately, for 10 min counting period at a depth of 15 μm from the surface, which nearly corresponds to the peak activation rate in Fig. 5. For actual application, it would be useful to cover the sample with a uniform foil with proper thickness during implantation in order to locate the peak of the activity distribution near the surface of the sample.

3. Summary and prospects

Thin Layer Activation (TLA) method for wear analysis for machine part was developed using implantation of intense RI beam as a tracer. Compared with the conventional method like "direct-beam activation" and "indirect activation", the present method using an in-flight RI-beam separator can provide pure RI tracer as beam with high energy and a wider selection of RI nuclides. The pure RI beam implantation can lighten the damage caused by radiation and heat for the material. The large penetration range of high-energy RI beam enables direct implantation of RI tracers to desired places in materials in atmosphere.

Beam development studies for intense RI beam production of ^{22}Na and ^{7}Be were performed. We have achieved the RI beam intensity of 2×10^{8}/s, approximately, for both beams. Both RI beams were extracted from vacuum to atmosphere and their energies were adjusted as suitable for near-surface implantation. To investigate an implantation-depth profile, an aluminum thin-foil stack was irradiated and was measured with Ge γ-ray detector. We could achieve peak activity of 1.3 and 0.08 (kBq/μm)/(1 pμA × 1 h irradiation) at 13 and 50 μm peak depth with 20 and 150 μm maximum depth from the surface for ^{7}Be and ^{22}Na, respectively. Thus, we can provide intense γ-ray activities at the near surface with a few 100 kBq in one-day beam time. According to these results, this method of activation looks promising for the wear diagnostics.

As we can provide different RI beams with controlling its implantation depth, some possible applications can be considered. Implantation of different RI for both machine parts contacting each other, one can distinguish the wear-loss rate of both interacting parts at the same time. Implantation of one or a few RIs with controlling its depth profile, it can be applicable for processing a wear-loss gauge on a machine part. It may help an effective maintenance and prevention of sudden failure of the machine systems.

Acknowledgement

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