APPLICATION OF SMALL ENERGY CYCLOTRONS FOR THIN LAYER ACTIVATION TECHNIQUE

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In many cyclotron laboratories the accelerator is partly used for industrial applications. One of these is the so called TLA (Thin Layer Activation) which is mainly used for wear (corrosion, erosion, ...) measurements. The samples in question (e.g. machine parts) are irradiated with appropriate particles and energy to reach their surface layer (100 nm to several microns) and produce radioactive atoms in it through nuclear reactions. By wearing the samples the radioactive label-atoms of the surface layer are removed together with the bulk of the sample. So, by using a calibration curve, from the change of the activity in the sample or in the removed material one can determine the quantity of the wear (corrosion, erosion).
Different methods were elaborated in our laboratory to investigate the wear of metals and otheractivatable matrices (with direct activation) and also for investigation of non-activatable samples (with nuclear implantation). Cross-section database was established for the most common nuclear reaction used in TLA.

1 Introduction

Reliable prediction and check of the wear of different machine parts is a very important task in engineering. Besides the conventional methods, nuclear methods are also used for this purpose [1-4]. The advantage of these methods is that the machine can run continuously during the measurement, without disassembling it. The method itself is based on the well established radio-tracer technique. Radioactive isotopes having relatively high energy gamma-radiation are introduced into the investigated surface of the sample in known quantity and with known distribution. These isotopes are removed during the wear/friction process together with the mass of the sample. From the measurement of the removed/remaining radioactivity the wear (material loss) can be exactly followed. The introduction of the labeling isotopes is normally achieved by irradiation of the sample with particle accelerators, where the matrix or trace elements of the sample are activated and form the necessary label isotopes.

Sometimes the major matrix or minor elements of the machine part to be investigated cannot be activated with the available bombarding particles at the available energies of the given particle accelerator. In this case, it is possible to introduce secondary radioactive particles from nuclear reactions. This method is also an appropriate solution when an extremely thin radioactive layer is necessary for testing.

A thin target (few tens of micrometers) containing the element **A** is bombarded by a beam of charged particles **a**, and the element **A** is activated through the nuclear reaction **A(a,b)B**. Some of the radioactive nuclei **B** have sufficient kinetic energy to leave the implantation target and to penetrate into the sample surface.

In the case of foil-target bombardment by light incident particles where the energy does not exceed 40 MeV, the energies of the recoiling radioactive ions **B** spread between a few hundred keV and several MeV. The maximum implantation depths in the material are between a few micrometers for medium mass radioactive nuclei (^{7}Be, ^{22}Na) and tens to hundreds of nanometers for heavier nuclei (^{48}V, ^{56}Co, ^{65}Zn).

The calibration procedure [4] varies in accordance with the implantation depth. If the implantation depth is in the micrometer range, the depth profile of the radioactive recoil nuclei can be determined by using the stacked foil technique [4-7]. Below the micrometer range, the calibration procedure is based on the thin film technique [9], where the composition of the film must be similar to that of the sample.

Wear measurements using TLA (Thin Layer Activation) are used in the authors' laboratory to test different machine parts made from metal (Fe, Ni, Cu, ...) and from super-hard materials (BN, artificial diamond, ...). For measurement of non-activatable (plastic, etc.) materials the technique of nuclear implantation has been developed. The advantages of this new method are that a unique type of activity can be produced; activation of very thin layers in the nm range is possible; thin layer activation of non–metallic materials can also be solved; radiation damage can be decreased under an acceptable level; production of the lowest measurable activity can be controlled.

2 Experimental equipment

2.1 Irradiation

The complexity of the experimental set-up depends on the task to be performed. In most of the experiment and practical cases a well focused high intensity charged particle beam is necessary to activate a given small part of the sample. The activated surface area spreads from several μm^2

to several cm^2. By scanning the beam or moving/rotating the sample in front of the beam line even much larger area can be activated. Fig. 1 .shows a typical irradiation geometry by TLA measurements.

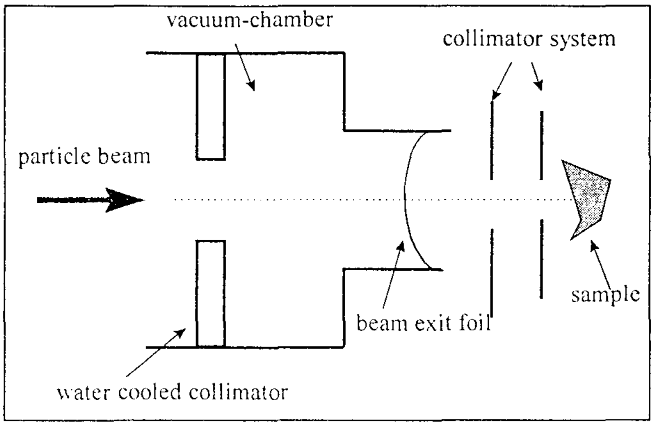

Figure 1 : Typical irradiation arrangement for Thin Layer Activation and wear measurements

Table 1: Recommended target-bombarding particle combinations and the produced isotopes

Element	Beam	Isotope	Half-life
Be	^{3}He	^{7}Be	53,3 d
C	^{3}He	^{7}Be	53,3 d
Mg	d	^{22}Na	2.62 y
Al		^{22}Na	2.62 y
Si	d	^{22}Na	2.62 y
Ti	p	^{48}V	16.0 d
V	d	^{51}Cr	27.7 d
Cr	p	^{52}Mn	5.7 d
		^{54}Mn	312.3 d
Mn	p	^{54}Mn	312.3 d
Fe	p	^{56}Co	78.5 d
		$^{58}Co + ^{56}Co$	
Co	p	^{58}Co	70.8 d
Ni	d	$^{58}Co + ^{56}Co$	
Cu	p	^{65}Zn	244.1 d
Zn	d	^{65}Zn	244.1 d
Zr	p	^{92m}Nb	10.1 d
Nb	p	^{92m}Nb	10.1 d
		^{95m}Tc	61 d
Mo	p	^{95m}Tc	61 d
Sn	d	^{124}Sb	60.2 d
W	p	^{184}Re	38 d

Most of the samples should be irradiated by external beam at atmospheric air pressure because of their sizes, but small samples/parts can also be put into the vacuum chamber to irradiate them in clean vacuum circumstances.

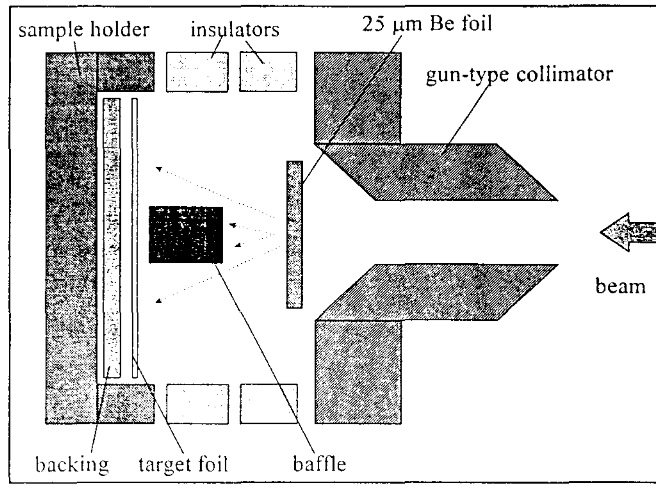

Figure 2 : Experimental irradiation equipment for nuclear implantation

If the direct beam can not produce suitable amount of radioactive isotopes at the given bombarding energy in the sample material itself, one can use the method of nuclear implantation to introduce secondary radioactive isotopes in a thin surface layer of the sample. An irradiation equipment for nuclear implantation is shown in Fig. 2

The frequently used implantation target is the beryllium producing ^{7}Be isotope with e.g. the $^{9}Be(^{3}He,\alpha n)^{7}Be$ nuclear reaction [12]. The product has 53 day half-life and 477 keV single gamma-line, which are suitable for thin layer activation and wear measurements. The possibilities for implanting other isotopes were also studied (e.g. ^{56}Co (half-life = 77 day) with the $^{56}Fe(p,n)^{56}Co$ nuclear reaction and ^{48}V with the $^{nat}Ti(^{3}He,x)^{48}V$ reaction.

2.2 Measurement

The irradiated or implanted samples are measured by gamma-spectroscopy systems at separate place after the irradiation. A typical measuring system used in experimental cases is shown in Fig. 3. This system is based on the relatively expensive semiconductor detectors. In this way very accurate separation and determination of the energies and intensities of the gamma-lines is possible, which is necessary in elaboration of a wear measurement process in a given practical case. If the method is elaborated and tested, one can use the much cheaper gamma detection system based on scintillation detectors and counters. This system is shown in Fig. 4. And it is capable for on-site use even in a running industrial plant.

3 Determination of the wear

With the experimental facility the amount of the different isotopes can be determined and a so called wear curve can be taken by using artificial wearing of the sample (polishing, slicing, etching, etc.). These curves correspond

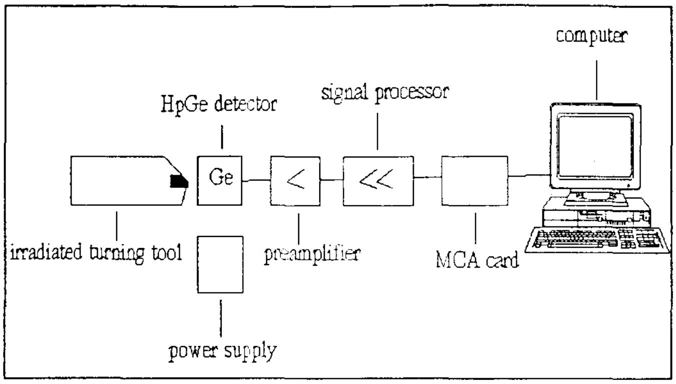

Figure 4 : Typical experimental gamma-spectroscopy system for measuring the activity and of irradiated TLA samples (e.g. the sample is a turning tool)

to a given material (single element or alloy). Measuring the change of the activity in industrial circumstances one can

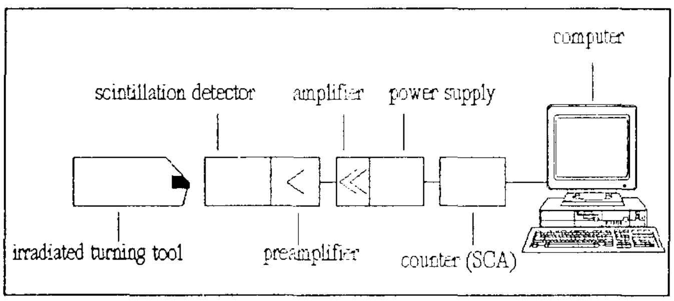

Figure 3 :Typical on-site wear measurement system with scintillation detector

determine the amount of wear (removed material) by using the experimental wear curves. A typical set of wear curves is shown in Fig. 5.

The wear curves can also be calculated from nuclear data

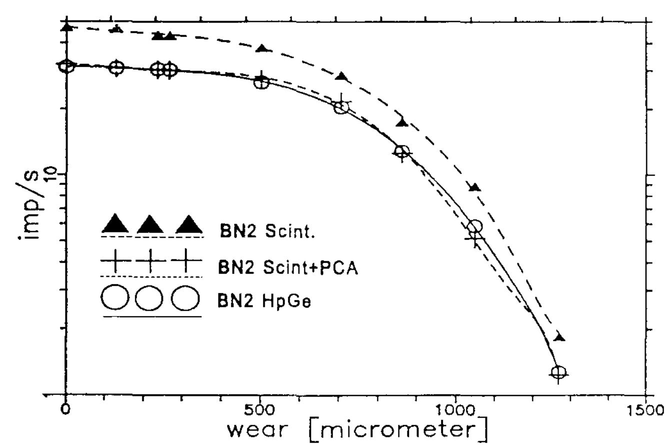

Figure 5 : Calibration curves for wear measurement determined by different measuring facilities.

such as cross section functions and the stopping power in the different materials. But because of the unreliability of these data these calculations show only the approximate trend of the wear curves.

4 Applications

There are two techniques in TLA application, namely the thin layer difference technique and the concentration measurement technique.

In the first technique, the activity of the irradiated machine part is measured by gamma spectrometry systems. The loss of activity is converted to the wear rate using the calibration curves. The sensitivity of this technique depends on the type of applications and a typical value of wear rate is around 0,01 mm/h.

In the second technique, the activity of the removed layer (e.g. wear products) is measured by one or more gamma spectrometry systems The activity of the wear products can be measured either in a special oil filter or in oil flow itself. This technique allows to monitor at least two wearing areas simultaneously.

The sensitivity of this technique for the typical cases is around 1 nm/h.

5 Conclusion

The Thin Layer Activation method is used in the industrial research and development in the developed and the developing countries. This method helps to increase the lifetime and reliability of various machines, installations and technological processes. At the same time the results obtained, for example, in automobile industry allow to design and to manufacture transport vehicles with low fuel consumption. The positive impact on the environment pollution has also been proved.

The main advantages of TLA are as follows:

- non-destructive remote monitoring of surface degradation, including wear, corrosion and erosion
- in-situ, on-line measurement of degradation of critical machine-parts in operation
- simultaneous measurement of surface degradation of several components in the same machine
- high sensitivity in monitoring the slow rate degrading processes
- no influence on the operating conditions of machine or system
- very low level of radioactivity (< 370 kBq(=10 mCi))
- cheaper and quicker compared to the conventional methods

The most promising areas for TLA applications are as follows:

Automobile and engine industry
piston rings (running surface, flanks)
piston ring groves

piston skirt
all kinds of bearings: crankshafts, camshafts, connecting rods, etc.
camshaft, camheads
cylinder liner
valve seat, valve shaft guidance
fuel injection nozzle, injection pump, fuel tubes
all kinds of gear wheels
gear and gear-parts

Pumps
all kinds of sealing-surfaces of the housing, blades, roller, wheelers, etc.

Turbines
blades, distance-pins, shaft-bearings

Refrigeration systems
compressor parts
piston skirts
cylinder wall
shaft bearings
rod bearings
blades
roller wheels and valves

Printing machines
needles, guidance, bearings

Textile machinery
Knitting machines: guidance, needles, connecting rods and bearings
Mills: bearings, shafts, guidance

Railway
wheel surfaces, brake discs, brake shoes, part of rails

Chemical industry
reactor vessel, tubes and pipes, valve system, nozzle

Oil industry
Test of anti-wear and anti-corrosion properties of lubricants
transport pipe-lines

Machinery
fabricating tools (turning tools, etc.)
bearings and other machine parts

Other
cooling systems with liquid metals

Acknowledgements

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