Irradiation of Machine Parts with Regard to Applications in Mechanical Engineering

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Abstract

The main emphasis in this paper is laid upon the production of radionuclides with the aid of charged particles. Some basic work as well as practical considerations about the activation with an external beam of a cyclotron are described. The final use of these radionuclides has been settled in mechanical engineering research - mostly for the detection of wear.

Typical irradiation targets are for instance combustion engine parts like cylinder liners, bearings, etc.. They are irradiated in thin surface layers only. The charged particles that bave been used are protons, deuterons and α-particles with energies between 10 - 50 MeV. The targets consist of all sorts of metals and alloys - Ti, Cr, Fe, Cu, Zn, Mo have been investigated so far.

In 1974 the activities of the "Laboratorium für Isotopentechnik" (LIT) at the Nuclear Research Center Karlsruhe in this field of application have resulted in a total irradiation time of 1000 hours at the cyclotron in Karlsruhe.

1. Methods of Wear Measurement with the Aid of Radionuclides

A method frequently used for wear measurements [1] consists of an arrangement of a wear test bench or an engine with a radioactive machine part in it, an oil circuit for the transport of the abraded wear to a measuring head for the detection of the γ-quanta, and an electronic and data processing unit. The radioactive machine part may be a bearing, a piston ring, a cylinder liner, an activated flank of a gear tooth etc..

During the test run the abraded wear particles are transported by the lubrication oil to the measuring head, where the γ-quanta emitted from these particles are detected. The machine parts to be investigated may be activated with charged particles in a thin layer at their surface or with neutrons in a nuclear reactor, where the bulk of the material becomes radioactive.

When no oil-circuit is available. as for example in the case of a Wankel-engine, the so called "thin layer difference method" may be applied for wear measurements. In this method the amount of wear is determined by the loss of activity of an irradiated part of an engine. The detector is set up outside the housing of the engine, but near the activated part. This part should only be radioactive in a very thin layer of about 20 - 100 μm.

Under the assumption that the debris produced during the test run is transported away and out of reach for the detector, the gradual loss of activity in the remaining layer is a measure for the wear incurred. It is necessary in this case to use thin layer activation with charged particles.
In both measuring methods proper calibration allows on-line measurement of wear, which is one of the main advantages of these methods.

2. Basis of Thin Layer Activation

When irradiating a thick target with the charged particles of a cyclotron, the particles are decelerated in the target to $E = 0$ at their range $X = X_E$. The energy curve can be computed by the Bethe-Formula [2]. Figure 1 shows the energy-curves for p, d, α-particles, related to their range. Table 1 gives the range values for some metals. The start energies refer to the cyclotron in Karlsruhe.

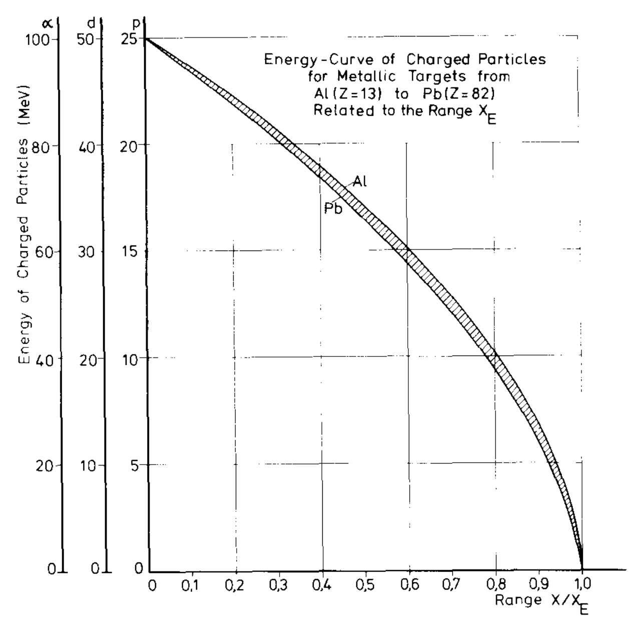

Fig. 1 Energy Degradation of Charged Particles.

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 514-517

Target	Protons 25 MeV	Deuterons 50 MeV	α-Particles 100 MeV
Al	3,280	6,570	3,225
Cr	1,448	2,900	1,422
Fe	1,336	2,676	1,312
Ni	1,171	2,344	1,149
Cu	1,226	2,455	1,203
Mo	1,221	2,444	1,197
W	0,817	1,636	0,800
Pb	1,456	2,913	1,425

Table 1 Range of Charged Particles in mm, Computed

A certain fraction of the penetrating particles will interact with the target atoms and produce radionuclides in the irradiated layer. Typical examples for the activation of iron are for instance:

$^{56}Fe(d,2n)^{56}Co$; $^{56}Fe(d,n)^{57}Co$;

$^{56}Fe(\alpha,pn)$ ^{58}Co etc.

The probability of these reactions is described by their cross sections or better their excitation functions, if the whole engergy range is taken under consideration.

Most reports on these subjects contain excitation functions of nuclear reactions which have been determined with isotopically enriched targets. In the applications we are dealing with, however, the metals involved always have natural isotope composition.

So the main interest is focused on the distribution of the radionuclides produced, whatever may have been the nuclear reaction. The exact predetermination of such a distribution for any target requires the knowledge of all relevant excitation functions. Programs are being written at present for this purpose.

In order to ascertain this knowledge experimentally, we have been employing two simple methods for the measurement of the activity depth distribution in the activated layer.

a) Irradiation of a stack of thin foils of the material (pure metal or alloy) to be investigated and postirradiation measurement of the single foils' activities.
The resulting curve S in Fig.2b represents the shape of the specific activity in the activated layer.

b) Irradiation of a thick target and subsequent grinding away of thin layers of the target in steps of 10 - 20 µm from $x = 0$ to $x = x_{max}$ (Fig.2b, T), and measurement of the residual activity in the target. The curve T can also be determined by integration of S. It represents the total activity distribution. Figure 2 shows a schematic survey of the relationships involved.

2a) Range-energy curve for charged particles [2)]

2b) Typical excitation function [3)]

2c) Specific and total activity distribution in the activated layer. The shape of the specific activity is closely related to the excitation function.

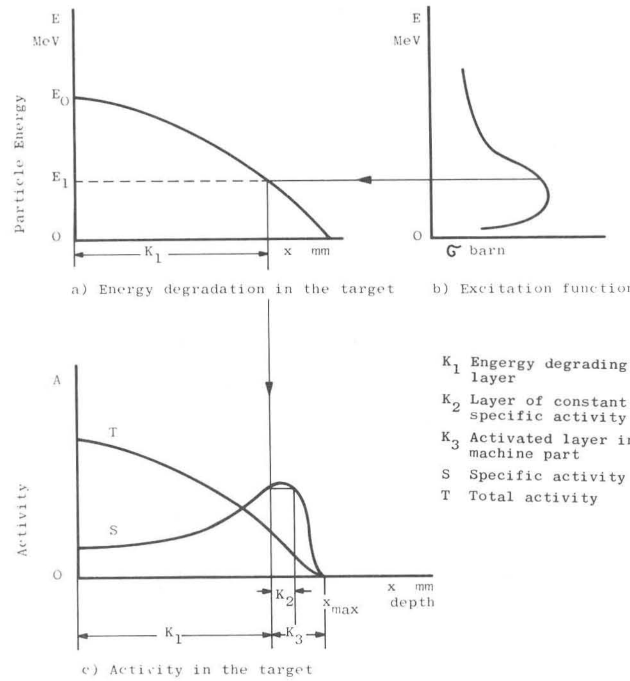

Fig.2 Dependencies of Thin Layer Activation (Schematic)

3. Experimental Determination of the Activity Distribution

Figure 3a shows the irradiation arrangement for the rod targets which are used for the determination of the curve T as described above. Fig. 3b shows the appropriate target for the measurement of the activity-yield of the radionuclides produced.

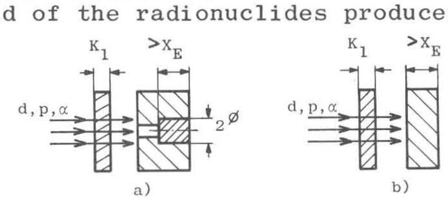

Fig.3 Rod Target for the Measurement of the Activity Distribution a) and Target for the Determination of the Activity Yield b).

This target's diameter is bigger in size than the beam diameter in order to collect all the charged particles. It is irradiated under recorded conditions of particle current (I in μA) and irradiation time (t in hours). The activity, produced in the target (A_1 in μCi) is measured at the end of irradiation and related to I·t. In a simplified form, valid to $t \ll T_{1/2}$, it follows for the activity yield A

$$A = \frac{A_1}{I \cdot t} \quad \frac{\mu Ci}{\mu Ah} \tag{1}$$

For a number of materials, enumerated in the abstract, the activity distribution and the activity yield were measured [4]. With the aid of these results and the energy-range conditions of Fig.1 and Table 2 the conditions of an irradiation can be selected. An example of an activity distribution is given in Fig.4 and the according activity yield in Table 2.

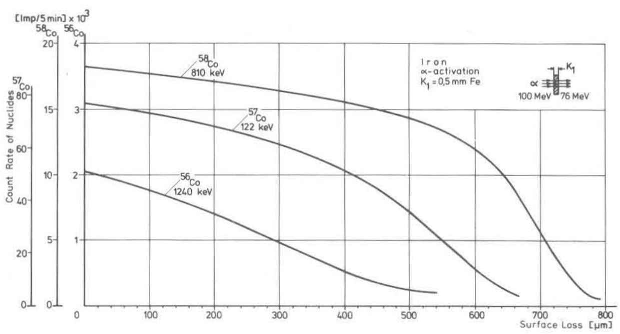

Fig.4 Activity Distribution in α-activated Iron

Target + Particle	Energy Degrading Layer	Nuclides Produced	Activity Yield A [μCi/μAh]
Fe + α	0,5 mm Fe	^{56}Co	14,2
E_o=100MeV	E_1=76 MeV	^{57}Co	13,4
		^{58}Co	37

Table 2 : Activity yield for α-activated Iron

Example: For a thin layer difference wear measurement an activity of A_1 = 100 μCi ^{58}Co and a linear range of about K_2 = 40 μm is required. I = 2 μA. Irradiation time t ?

Solution: The thickness of the degrading layer must be (cf Fig.4):
$K_1 = 0{,}5 + 0{,}68 = \underline{\underline{1{,}38\ mm}}$
The yield A at the surface loss 680 μm will be 40% of the total value of 37 μCi/μAh.

The irradiation time becomes:

$$t = \frac{A_1}{A \cdot 0{,}4 \cdot I} = \frac{100\ \mu Ci}{37 \mu Ci/\mu Ah \cdot 0{,}4 \cdot 2 \mu A} = \underline{\underline{3{,}4\ h}}$$

4. Practical Facts on Irradiations

The choice of the irradiation conditions (d,p,α, Energy) depends on the radionuclides induced in the material, of their half-lives, their activity yields, the availability of the cyclotron [4]. For measuring purposes, that demand the thin layer difference method, it is often propitious to have only one single radionuclide in the layer in order to facilitate the halflive-corrections. For the other wear test method where the radioactive wear particles are measured, this restriction is not much urgent, because in this case calibrations can be executed quickly. In any case, however, the specific activity schould be constant in the layer supposed to be worn away.

It has already been shown in the example, that the beam energy should be chosen so that the linear range of high specific activity lies in the surface of the target. This is one of the reasons why in the example ^{58}Co had been prefered to ^{56}Co or ^{57}Co. More details on this behalf can be found in [4] and [5].

When there is no energy-variable cyclotron available [6] the energy E_1 required for activation can be degraded from the start energy E_o by arranging a layer of suitable thickness K_1 in front of the target. This layer can be made of the same material as the target to be irradiated, or of any other material with some other equivalent thickness. Aluminium has successfully been used because of its high thermal conductivity. Moreover the radionuclides produced in Al possess short half-lives, so that the material can be reused.

It should be noted that the particle beam is widened in the degrading layer. The original beam diameter may often be only a few millimetres whereas the area to be activated is several square-centimetres. When arranging the target at a distance of some centimetres apart of the degrading layer, it may gain the desired uniform activity on an area greater than the original beam area. A uniform activity may also be attained with the aid of a beam scanning system or with a manipulator system that revolves or moves the target in front of the beam. This later solution is used in our institute.

The beam current to be applied depends on the material properties, target size, cooling, and amounts to about 1 - 3 μA. Compressed air cooling of the targets can be recommanded during irradiations. A rough indication of irradiation time may be

1 - 8 hours for the targets mentioned initially. The activities produced are of the order of 50 - 500 μCi, only. Severe handling problems don't exist.

For purposes of calibration with regard to the applications, it is beneficial to irradiate thin samples (a few milligrams) of the target material together with the target. The sample will then receive the same specific activity as the target at the surface. If the target material is available in thin foils, a piece of such a foil can be fixed upon the target. The quality of an irradiation can then easily be controlled by preparation of an autoradiography of the foil. We were able to show that the area density distribution is proportional to the specific activity of the targets surface [7].

5. Examples of Activation

Figure 5 gives a view of the outlet window of the cyclotron's beam tube. A pinion to be activated is mounted on the manipulator device. One tooth flank was irradiated with deuterons for 10 hours. Fig.6 shows the arrangement of a railway wheel prior to activation.

Besides the application for wear measurements the thin layer activation is a useful tool for the radioactive marking of machine parts in order to execute speed measurements. A schematic representation of this method is shown in Fig.7. Among other applications the speed of the cage of a roller bearing of a jet engine was successfully measured with this method.

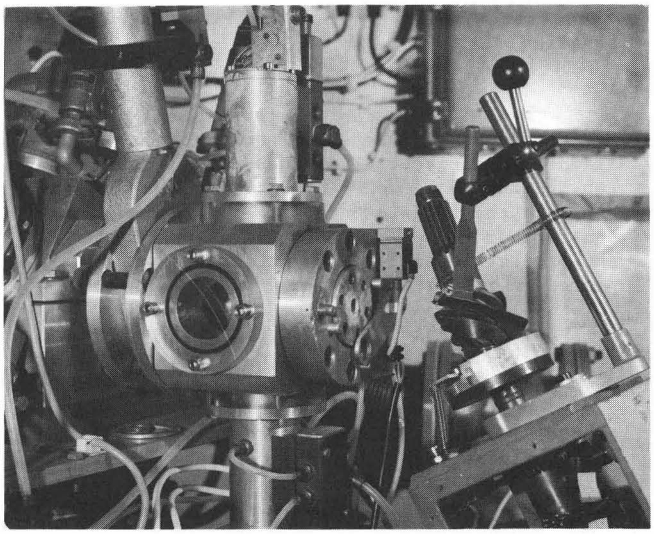

Fig.5 Activation of a Pinion

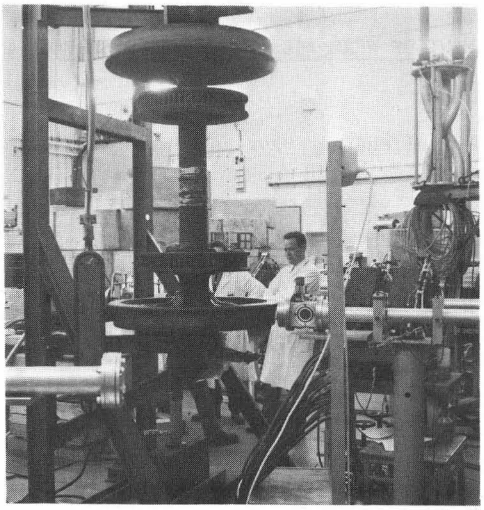

Fig.6 Railway Wheel Prepared for Activation

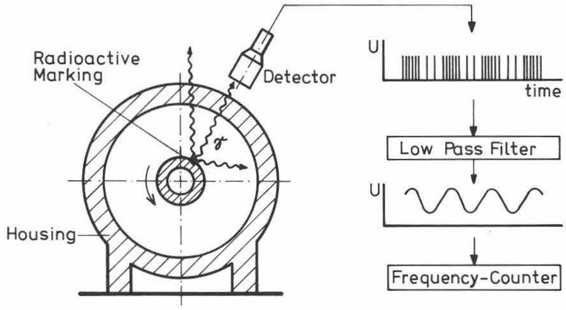

Fig.7 Principle of Speed Measurement. Radioactive Marking with Thin Layer Activation

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