THE APPLICATION OF CYCLOTRON IN MECHANICAL ENGINEERING

P. Fehsenfeld, A. Kleinrahm
Kernforschungszentrum Karlsruhe GmbH
Institut für Kernphysik III/Zyklotron
D-7500 Karlsruhe, Postfach 3640, Federal Republic of Germany

ABSTRACT

A subject of increasing application of cyclotron machines is the "Radionuclide Technique in Mechanical Engineering" (RTM), a measuring system that enables wear and corrosion diagnostics of components of operating machines, apparatus or processing plants. The three components of the RTM-system, the thin layer-activation at the cyclotron, the measuring methods and the measuring instruments for application in industry, have been developed systematically at KfK over more than 15 years and are being used increasingly by industry in Germany, Japan and the United States.

The present development of RTM to modern problems in engineering and material research as well as the successful application in new industrial areas will be reported.

1. INTRODUCTION

The working principle of RTM may be illustrated by the example of a combustion engine, very schematically delineated in Fig. 1 by the piston ring, the cylinder wall, the cooling water jacket and the housing wall. Subject to wear measurement is the cylinder wall, which has been labelled in its critical zone around the upper dead point of the piston ring by thin layer activation at a cyclotron. The thickness of the radioactive surface layer is adjustable to within 20 micrometer and around 0.2 mm according to the expected wear measurement depth.

The characteristic gamma radiation emitted from the labelled zone of the component penetrates the cyclinder wall, water jacket and housing wall without major attenuation and is recorded by a radiation measuring equipment (detector) appropriately located outside the machine, as indicated in Fig. 1 (upper part). The lower part of the figure shows a simplified calibration curve of the measured radiation intensity (or total activity) versus depth in the material. Thus the wear of the component can be observed easily and exactly via the variation of the activity caused by loss of material.

The measured radiation values are converted into wear values by a computer, integrated in the measurement equipment and displayed in a comprehensible and informative manner. With these introductory explanations of the function principle, it is evident that RTM is not only "thin-

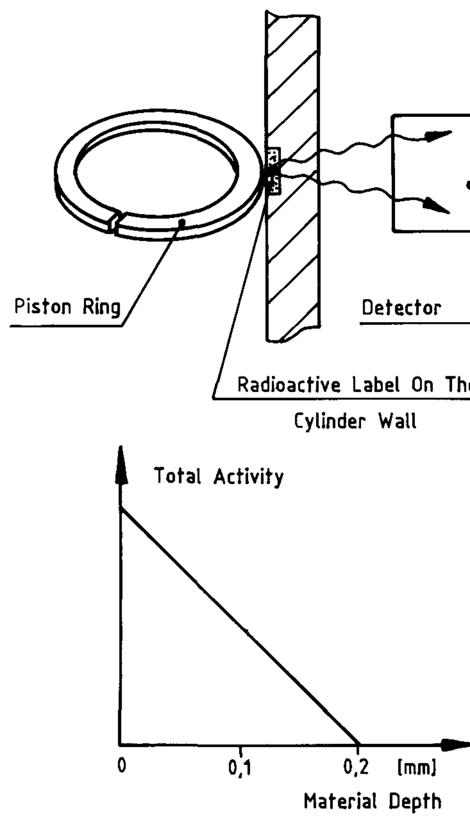

Fig. 1: Working principle of RTM:
The activity of the cylinder wall is monitored by a detector outside the engine. The lower part shows a simplified calibration curve of total activity versus material depth.

layer activation" but represents a technical system consisting of the three components

- Measuring Methods
- Measuring Instruments
- Thin Layer Activation Technique (TLA)

which are interrelated to each other.
Basic know-how and data as well as technical equipment to each of the three components of RTM have been developed continuously at KfK over the recent years to reliable applications in industry, engineering research and development.

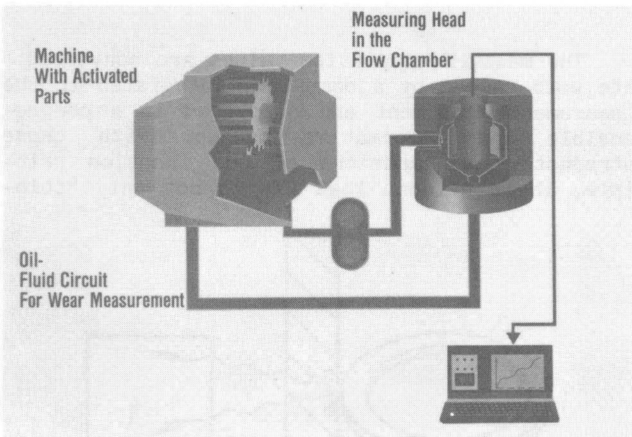

Fig. 2: The concentration measurement method (CMM).

2. THE COMPONENTS OF RTM

2.1 Measurement Methods

There are basically two methods which are applied in registering wear of an irradiated part, the measurement either of the activity removed from it (henceforth called the concentration measurement method (CMM)) or of the residual activity (the thin layer difference method or direct measurement method (DMM)). The first method is shown schematically in Fig. 2. The oil that lubricates the part or parts under study (tooth wheel and wheel bearing in Fig. 2) is pumped in a closed circuit and passes by a gamma ray detector in a flow chamber, which measures the activity of the wear particles suspended in the lubricant. Since the wear particles can be assumed to be distributed homogeneously and a constant fraction of the oil surrounds the detector the countrate is proportional to the total wear after the start of the experiment. The second method has already been mentioned in the introduction and is illustrated by Fig. 3. The activity of the irradiated part inside the machine is measured by a gamma ray detector close to the machine. In both types of measurements one has to make sure, of course, that the wear particles are removed from near the part under investigation. In some cases, such as wear of railway wheels, the direct measurement method is the only one which can be applied because the wear particles are inevitably dispersed.

The wear resolution capacity of both measurement methods is in the region of nanometers or nanograms at measuring times of some minutes and activity levels of the labelling around 0.1 millicurie (= 4 MBq). Both measurement methods have been developed by KfK to high performance and used in industry for more than ten years. The concentration measurement method is patented by KfK.

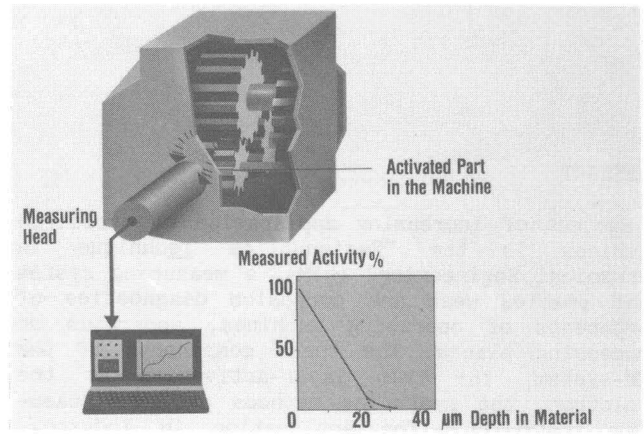

Fig. 3: The thin layer difference method.

2.2 Measuring Instruments

The activity is measured almost exclusively by Sodium-Iodide-Detectors (NaI(Tl)). Germanium detectors offer a much better gamma energy resolution for wear studies with different radionuclides but they suffer from the sensitivity to shock and vibrations and the need of cooling by liquid nitrogen, often not available in industry.

So the instrument consists of conventional radiation measurement technique with a special fastpulse electronic fulfilling the following requirements:

- reliable counting of statistical pulse rates up to 300 kHz
- automatical dead-time correction
- temperature-compensated spectrum stabilizer
- on-line display of the wear propagation
- reliable operation under industrial environmental conditions

The measuring systems developed at KfK are manufactured and marketed by two different firms in licence of KfK.

2.3 Thin-Layer Activation

2.3.1 Basic physical considerations

The physical background of thin layer activation process is well known and will be described briefly by the example illustrated in Fig. 4. When fast charged particles from an accelerator enter a solid they are slowed down in a well-defined way. The particles usually employed in this type of study, mostly protons, deuterons and ^{4}He at energies between 6 and 100 MeV, come to rest at depths of the order of a millimeter below the surface. In the upper part of Fig. 4 the

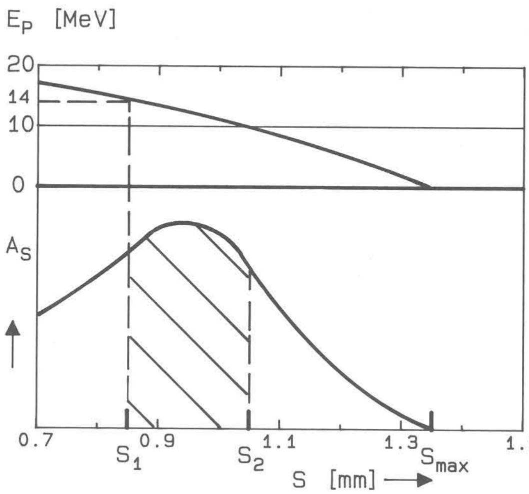

Fig. 4: Dependence of proton energy (upper part) and activity concentration (lower part) on depth for an irradiation of iron by 30 MeV protons. Only the last part of the range is shown. The hatched area indicates the depth range of approximately constant activity concentration.

decreasing energy of protons over the travelling distance in iron, zero energy at the range of 1.35 mm is shown. Some of the protons interact with the ^{56}Fe-nuclides of the iron material resulting in the production of the radioactive nuclides ^{56}Co, via the ^{56}Fe(p,n)^{56}Co reaction. These radioactive nuclides represent the labelling which is used in the wear studies. The cross section for the production of ^{56}Co in iron material by proton changes drastically with the energy of the particles, resulting in the marked variation of the induced activity with depth. This is illustrated in the lower part of Fig. 4. The hatched area of the activity distribution indicates the depth range of approximately constant activity concentration. By choosing the suitable energy of the incident protons (in Fig. 4): Ep = 14 MeV - a layer of homogeneous activity concentration at the surface can be achieved. The quality of this procedure is demonstrated by

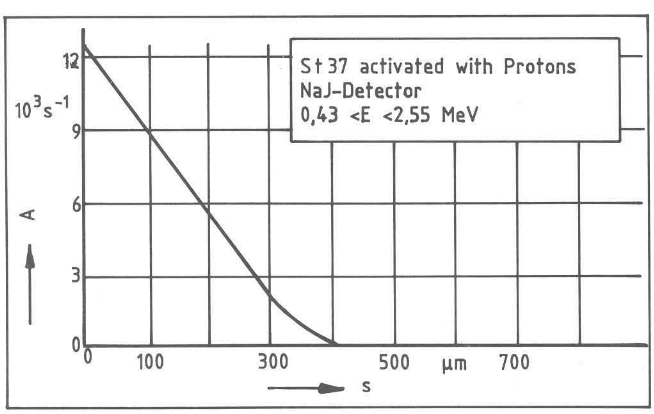

Fig. 5: Total activity versus penetration depth for 14 MeV protons in steel (ST 37).

Fig. 5 showing the measured total activity (A) of ^{56}Co versus depth (S, micrometer) in a steel (ST 37) sample activated by 14 MeV protons.

Within a depth range of 200 micrometer at the surface the correlation between measured activity and material loss is strictly linear.

The thickness of the homogeneous activity layer can be varied by different technical means in the range between 20 micrometer and 1 millimeter just according to the requirements of the wear measuring problems. The chemical composition of the material to be activated is determined by engineering design considerations in virtually all cases. The physicist therefore has to choose the kind of particle and energy best suited for the material under study. This may be a complicated task because usually several different radionuclides with differing depth distributions are produced in the material. These make decay corrections complicated even in simple measurements, and frequently it is necessary to determine the depth distribution by experiment. This can be done by irradiating a small pin made of the same material, grinding off the surface step by step and measuring the residual activity each time.

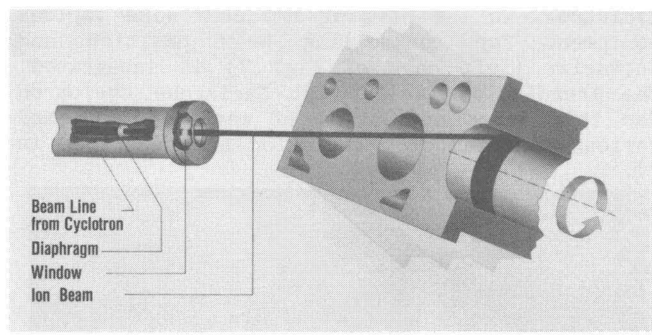

Fig. 6: Irradiation of an engine block: precise and uniform labelling on the cylinder bore for wear measurement in the T.D.C. of the first piston ring ("gusset wear").

In many cases it is possible to produce different radionuclides (even in the same material) by choosing the energy and the bombarding particle appropriately. This allows a simultaneous measurement of wear on different parts of the machine if the characteristic γ-radiations of the radionuclides can be separated.

The irradiation parameters and technique have been developed at KfK for thin layer activation of all industrial iron and steel grades, low-alloy steels up to high-alloy steels, non-ferrous metals and their alloys of Aluminium, Cobalt, Chromium, Copper, Molybdenum, Nickel, Lead, Tin, Vanadium, Tungsten, Zinc, sintered and hard metals and ceramic materials. Only the plastics and elastomers cannot be activated because of the modification of their mechanical properties when irradiated with charged particles.

The development work in thin layer activation has always been accompanied by investigation of damage in activated materials. The radiation dose of charged particles applied for thin layer activation is in the case of metals usually by a factor of 10^{-3} to 10^{-4} less than the critical dose at which radiation damage may occur and in the case of ceramics sometimes only 10^{-1} of the critical dose. Hence routine tests for radiation damage in ceramics have been introduced.

2.3.2 The irradiation of machine parts

Thin layer activation of a larger machine part may be demonstrated by the irradiation of a cyclinder block of a combustion engine illustrated schematically in Fig. 6. The beam from the cyclotron, 3 to 5 mm of diameter, leaves the evacuated beam tube through a thin metal window and hits the cylinder bore of the engine block adjusted at a distance of 150 mm in front of the tube head. The engine block rotates precisely around the axis of the bore. The incident ion beam produces a regular, annular label in the Top Dead Center (TDC) of the piston ring. The precise labelling enables the directed wear measurements under real operation conditions. Very fast and reliable optimization to long lived components of the system piston ring-cylinder wall is possible. Fig. 7 shows the rotating engine block in front of the beam line of KfK Cyclotron. In the head of the beam line various equipment for controlling beam position and intensity (left part of Fig. 7) is integrated. The irradiation facility at Karlsruhe Cyclotron for thin layer actication of machine parts and various examples of irradiation are described in 1).

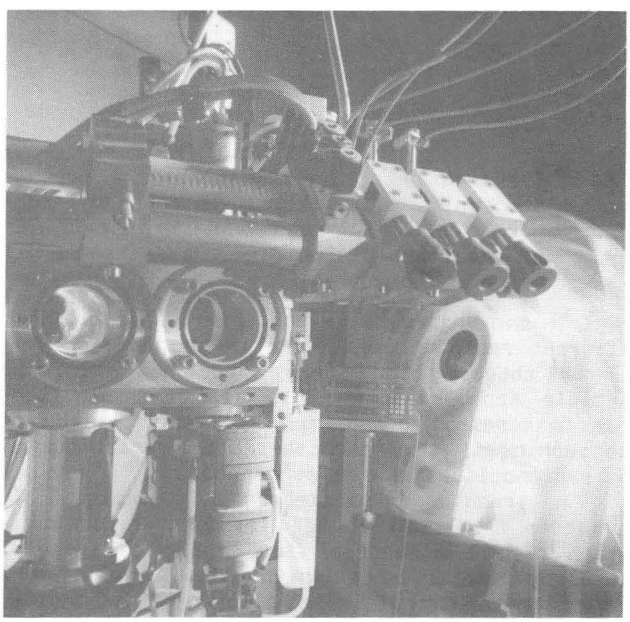

Fig. 7: Irradiation of an engine block at the cyclotron:
The engine block rotates around the axis of the bore. The incident ion beam produces a regular annular label in the T.D.C. of the piston ring. The precise labelling enables the directed wear measurements under real operation conditions and with that the very fast and reliable optimization to long-lived components of the system piston ring-cylinder wall.

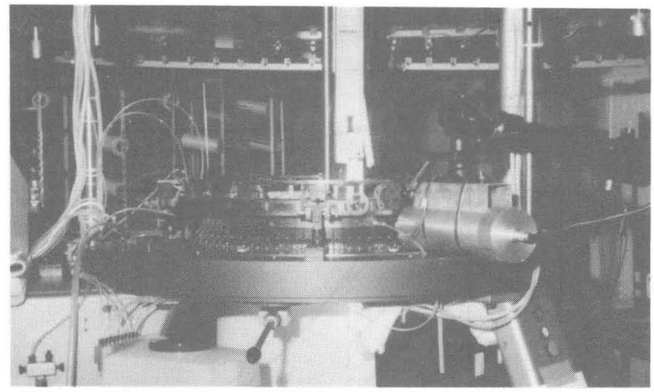

Fig. 8: Wear measurement at a knitting machine.

3. RECENT DEVELOPMENTS

3.1 New Areas of Industrial Applications

Textile and chemical industries are using advanced techniques. On the interest of these branches the activation technique and the measuring methods have been adapted to their special requirements. An example for application of these developments is demonstrated in Fig. 8 showing the setup for the wear measurement of a needle guidance system of a high speed knitting machine at the Institut für Textil Technik, Denkendorf. Needle guidances of different materials have been investigated. The result of the measurement, illustrated in Fig. 9, was an improvement of the machine service life by a factor of seven.

RTM enables a wear rate resolution down to few nanometer per hour.

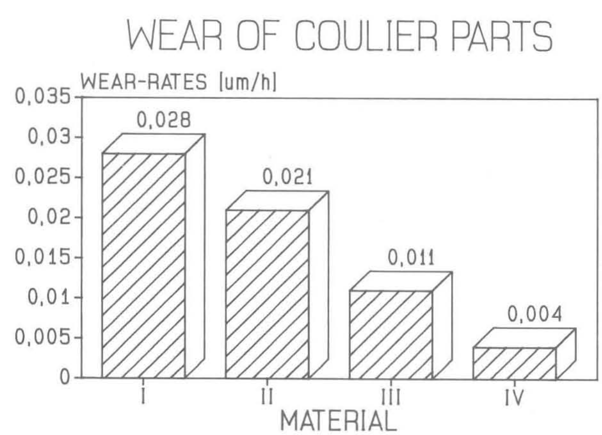

Fig. 9: Wear rates for different materials of the needle guidances in a knitting machine.

3.2 Thin Layer Activation Technique for New Materials

Ceramics, cermets and hardcoatings are increasingly in use for the construction of modern engines, machines and apparatus. The enormous wear resistance of these new materials requires a sensitivity of the wear measurements - inevitable for development work - that can be achieved only by RTM.

Adequate irradiation procedures for thin-layer activation of the essential materials Al_2O_3, SiC, Si_3N_4, ZrO_2, TiC, TiN, cermets and a various types of coatings have been developed in cooperation with several industrial companies (Daimler-Benz AG, Detroit Diesel Corp., Feldmühle-Plochingen, Krupp-Essen) and material research institutes (IMF-KfK/Karlsruhe, MPA-University-Stuttgart). The developed activation technique has been successfully applied in wear measurements of these modern materials in industry and research laboratories.

A typical example for thin-layer activation of ceramics is illustrated in Fig. 10 by the activity-depth profile of ^{22}Na in Al_2O_3. The region of strict homogeneously distributed activity over S_M=45 µm near the surface, well suited for precise wear measurements, is demonstrating the high quality of activation technique.

There are still two problems remaining to be solved in further development work:

a) The minimum thickness of radioactive layer in some ceramics is limited to about 40 microns. Preferably a layer of 10 microns to 20 microns should be achieved because of the gain in sensitivity of wear measurement.

b) The yield for the production of suitable radioactivity in Al_2O_3, SiC, Si_3N_4 is as low as 3 % to 5 % of the yield of ^{56}Co in iron. The results are long irradiation times at the cyclotron and therefore high costs for the activation of these materials.

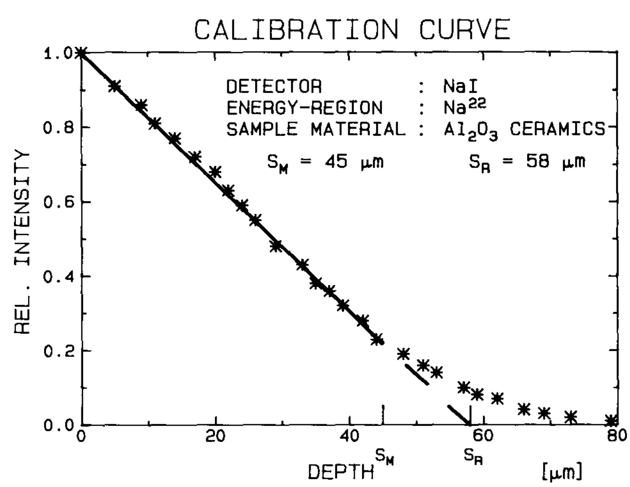

Fig. 10: Activity-depth profile of ^{22}Na in Al_2O_3.

The most efficient technique for the achievement of the desired extreme thin layer activation of ceramics may become the ^{7}Be- and ^{22}Na-Ion-Implantation, which is under investigation at Michigan State University [2] as well as at KfK-Research Center. This activation method may also be suitable for the radioactive labelling of plastic materials, that could not be activated up to now because of its high sensitivity to radiation damage.

REFERECNES

1) V. Bechtold, P. Fehsenfeld, H. Schweickert 12th Int. Conf. on cyclotrons and their applications, Tokyo 1989, pp. 593-596

2) M.L. Mallory, this conference