RADIONUCLIDE TECHNIQUE IN MECHANICAL ENGINEERING*)

P. FEHSENFELD
Forschungszentrum Karlsruhe, Postfach 3640, D-76021 Karlsruhe, Germany, e-mail: Peter.Fehsenfeld@hzy.fzk.de

C. EIFRIG
Labor für Verschleißtests, L.-Frank-Straße 59, D-04318 Leipzig, Germany

U. KREMLING
IMA Materialforschung und Anwendungstechnik GmbH, PF 800144, D-01101 Dresden, Germany

R. KUBAT
Forschungszentrum Karlsruhe, Postfach 3640, D-76021 Karlsruhe, Germany

SUMMARY

RTM - Radionuclide Technique in Mechanical Engineering represents a high sensitive wear diagnostics, well introduced and widely used for research and development work of the industries in Europe, North America and Japan. The RTM is now extended for advantageous application in biomechanical engineering. First on-line wear measurements at a hip joint simulator of IMA Dresden are reported.

Keywords: wear, corrosion, radionuclide technique, biomechanical engineering, hip joint prostheses

1 INTRODUCTION

A subject of increasing use for solving tribological problems in industry in Europe, Japan and the United States is the "**R**adionuclide **T**echnique in **M**echanical Engineering" (RTM), a measuring system that enables wear and corrosion diagnostics of vital parts during operation in machines, apparatus or processing plants.

The high precision wear measurement technique is now extended for advantageous application in biomechanical engineering.

2 RTM MEASUREMENT METHODS

The working principle of RTM may be illustrated by the example of a combustion engine, very schematically delineated in Figure 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 radioactive labelled in its critical zone around the upper dead point of the piston ring by thin layer activation at a cyclotron.

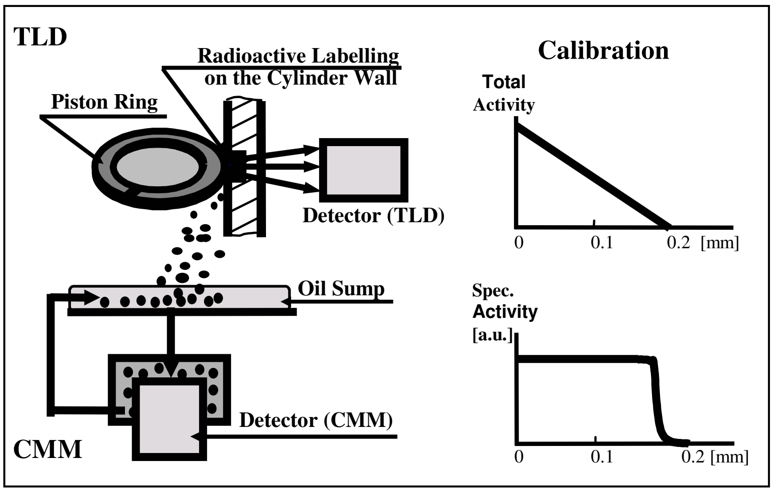

Figure 1: Working principle and measurement methods of RTM for the example of a schematised combustion engine: Thin Layer Difference Method TLD: The activity of the cylinder wall is monitored by a detector outside the engine. The calibration curve demonstrates the linear relation between measured activity and wear depth. Concentration Measurement Method, CMM: The wear particles are suspended in the lubricant which is pumped through the flow chamber with the detector. The count rate of the detector is proportional to the total wear.

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The thickness of the radioactive surface layer is adjustable within 20 µm and around 0.2 mm according to the expected wear measurement depth.

The characteristic gamma radiation emitted from the radioactive labelled zone of the component penetrates the cylinder wall, water jacket and housing wall without major attenuation and is recorded by a radiation measuring equipment (Detector TLD) appropriately located outside the machine, as indicated in Figure 1 (upper part, left). The right side of the figure shows a simplified calibration curve of the measured radiation intensity of total activity versus depth in the material. Note the linearity of the slope of the calibration curve.

Thus the wear of the component can be observed easily and exactly via the variation of the activity caused by loss of material. This kind of measurement is called the **T**hin **L**ayer **D**ifference Method **TLD.**

The **C**oncentration **M**easurement **M**ethod **CMM** is illustrated schematically in the lower part of Figure 1. The oil that lubricates the part or parts under study 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 count rate is proportional to the total wear after the start of the experiment.

The wear resolution capacity of both measurement methods is in the region of nanometers or micrograms at measuring times of some minutes and activity levels of the labelling around 1 MBq. Both measurement methods have been developed at Forschungszentrum Karlsruhe to high performance and are used in industry for more than ten years.

3 THIN LAYER ACTIVATION

Radioactive Labelling by **T**hin **L**ayer **A**ctivation (**TLA**) is based on nuclear reactions of fast charged particles – protons, deuterons, alpha particles at energies between 6 and 100 MeV – in solid materials. The procedure may be explained for the usual case of iron material. With the external directed beam of 14 MeV protons from the cyclotron a homogeneous layer of ^{56}Co via the reaction $^{56}Fe(p,n)^{56}Co$ is produced in the surface of the iron target. The thickness of layer can be varied between 20 and 200 µm by using the adequate angle of incidence and energy of particles. The physical and chemical properties of metallic materials are not affected by TLA.

TLA technique has been developed at Karlsruhe Cyclotron for all industrial iron and steel grades (low-alloy steels up to high-alloy steels), non-ferrous metals and alloys: Al, Co, Cr, Cu, Mo, Ni, Pb, Sn, Ti, V, W, Zn, sintered and hard metals, ceramics.

As an example of machine part irradiation is illustrating Figure 2 an engine block activation in the external beam at Karlsruhe Cyclotron.

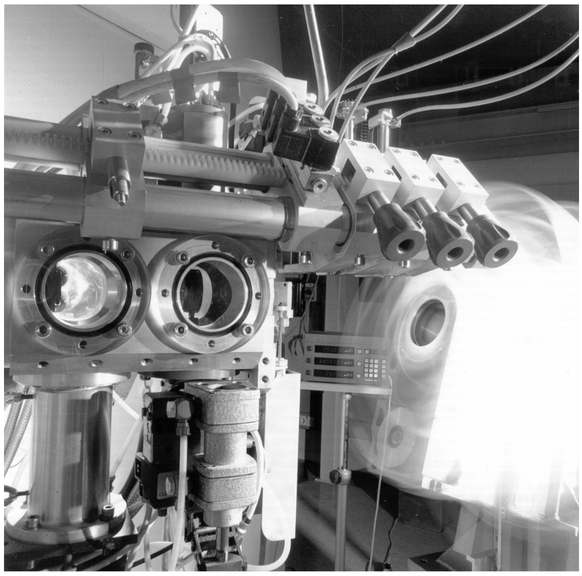

Figure 2: Activation of an Engine Block
The engine block rotates around the axes of the bore. The incident ion beam of the Karlsruhe Cyclotron produces a precise regular labelling in the T.D.C. of the piston ring.

TLA cannot be applied to synthetic materials, plastics, polymers, elastomers. These materials merely consisting of carbon and hydrogen can hardly be activated by charged particle irradiation and more over they are extremely sensitive to radiation damage.

A suitable mild method for radioactive labelling of synthetic materials by radioactive ion implantation is under development but is not yet routinely available.

4 EXAMPLE OF WEAR MEASUREMENT

RTM is widely used as a tool for wear analysis of engine components such as bearings, gears, camshafts, valves, tappets, pistons, cylinder walls etc., but it is now also being used to evaluate corrosion and erosion phenomena in pipes, vapour and gas turbine blades, offshore platforms and sea bed pipe work, in Chemical and Textile Industry.

A typical result of an RTM application is given in Figure 3 for the case of wear measurements at a high speed knitting machine. The needle guidances are the critical, stand time limiting components of the machine. Guidances of four different materials were investigated. The results demonstrate the wear rate resolution down to few nanometers per hour.

From an RTM wear test over two weeks an improvement of the machine service life by a factor of seven was achieved

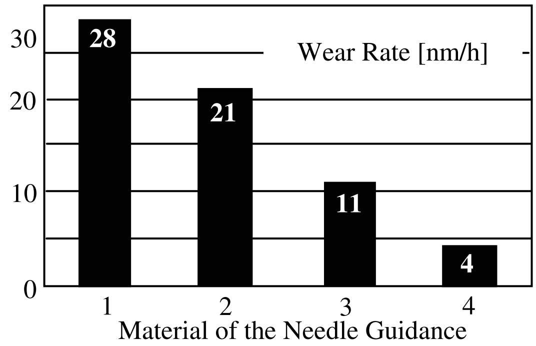

Figure 3: Wear measurement results of a high speed knitting machine demonstrating the sensitivity of RTM, wear rates in nanometers (nm) for different materials

5 THE APPLICATION OF RTM TO PROSTHETICS

The RTM method is now extended to the solution of world wide problems in development of modern materials (synthetic materials, ceramics, hard coatings etc.), their industrial application, and in biomechanical engineering especially prosthetics:

The number of surgeries for total replacement of bone joints by prostheses increases continuously. One reason is the limited life time of the actual hip joint prostheses which requires a considerable number of revision surgeries. Wear particles are assumed as the main reason for the late aseptic slackening of the implants. So a sensitive and reliable measurement of wear is required for the improvement of the life time of prostheses.

An on-line wear diagnostic system for the development of longer living artificial hip and knee joints was established using the know how of RTM method. Figure 4 is demonstrating the special Concentration Measurement Device connected to a hip joint simulator.

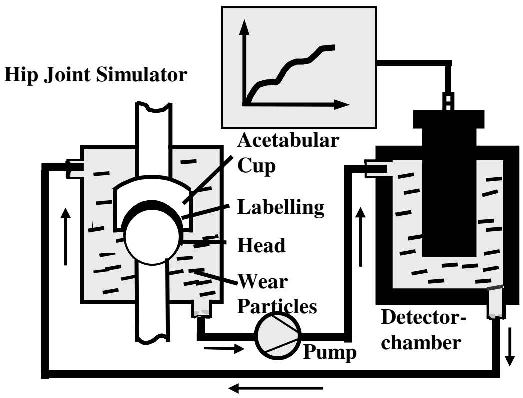

Figure 4: Measuring principle of RTM for biomechanical engineering

The basis of the system is the new radioactive labelling technique for prosthetic components of metallic and ceramic materials.

The established measuring method enables complete wear analysis with a resolution as high as 0.1 µg of wear mass respectively several nanometres in depth (for metallic components).

In a cooperation with IMA Anwendungstechnik und Materialforschung GmbH, Dresden, the world wide first on-line wear measurement was performed using this wear diagnostic system for prosthetics, coupled with the hip joint simulator at IMA Test Laboratory.

An Al_2O_3 ceramic-ceramic combination for acetabular cup and the head (28 mm diameter) of the hip joint was used in the wear test. Three heads got a radioactive labelling of Sodium 22 (Na-22, half life = 2.6 years, activity = 0.6 MBq) by thin layer activation at Karlsruhe Cyclotron. The radioactive zone of 10 cm^2 was centred around the point of maximum load attack from the cup. The depth of the homogeneous labelling into the ceramic material was around 140 µm.

The wear tests were performed at different upper/lower load on the joint 2.5/0.5 kN and 3.0/0.3 kN, at different frequencies 1 Hz and 2 Hz, in a start / stop mode and for changing the joint surrounding medium aqua dest. to bovine serum. The example of results in Figure 5 demonstrates the wear behaviour of a joint (frequency 1 Hz, in aqua dest.) with a weak not precise fixation of the head stem with an extremely high run-in wear rate of 38 µg/3600 cycles followed by a nearly constant wear region of 0.3 µg/3600 cycles at a load of 2.5/0.5 kN. After 60,000 cycles the load was raised to 3.0/0.3 kN. The wear rate increased by 66 % to 0.5 µg/3600 cycles. Following wear rates of run-in process in aqua dest., load: 3/0.3 kN, frequency: 1 Hz, could be observed.

Wear Rate [µg / 3600 cycles]	Remarks
13	at the start of a new, more precise fixation of head and cup No. 1
0.4	head and cup No. 2
0.09	head and cup No. 3

Table 1: Wear rates of run-in process, linear fit over several hours measuring time

The run-in period was followed by a phase of nearly constant wear rates (conditions: aqua dest., 3 / 0.3 kN, 1Hz) of

Wear Rate [µg / 3600 cycles]	No. of joint
0.3	1
0.04	2
0.00	3

Table 2: Wear rates after run-in, linear fit over several days

At the end of the wear test of joint No. 3 the aqua dest. was exchanged for bovine serum. The linear fit over a measuring time of 40 hours respectively 80 hours resulted wear rates of (0.008 ± 0.006) µg/3600 cycles and (0.006 ± 0.009) µg/3600 cycles.

The wear measurements of joint No. 1 at the different frequencies resulted decreasing wear rates from (0.3 ± 0.08) µg/3600 cycles at 1 Hz to (0.08 ± 0.03) µg/3600 cycles at 2 Hz. That is a decrease of 70 %.
A subsequent start / stop mode over 6 hours – every 10 minutes the simulator was stopped for one minute then started again - increased the wear rate from 0.08 µg/3600 cycles to (0.55 ± 0.25) µg/3600 cycles.

The surface roughness (R_a and R_{zmax}) was measured at IMA Tribology Laboratory before (except joint 1) and after the wear test at three different spots in the cups of the joints No. 1 – 3. The mean values for R_{zmax} are listed in Table 3 together with the total number of cycles for the wear test of each joint. By far the most smooth surface of the cup before as well as after wear test was stated for joint 3. Also the head and the cup of this joint were fitting most accurately to each other.

Joint No.	R_{zmax} / µm before test	R_{zmax} / µm after test	Number of Cycles
1	-	0.598	875,000
2	0.166	0.285	1,335,000
3	0.053	0.147	754,800

Table 3: Surface Roughness of the cups before and after test (mean value of R_{zmax} at 3 different spots)

From these first on-line wear tests with radionuclide technique following preliminary conclusions may be drawn.

- Weak imbedding of the femoral stem and/or not precise adjustment of the head and the cup to each other may produce severe wear of at least one order of magnitude higher than for precisely imbedded and adjusted joint components.
- The expected influence of surface roughness on the wear process was stated.
- Higher frequency may decrease the wear significantly.
- Raising of load may increase the wear.
- A start/stop mode resulted higher wear rate.
- A difference of wear for the different media aqua dest. and bovine serum was not evident within the measurement accuracy of 10 nanograms.

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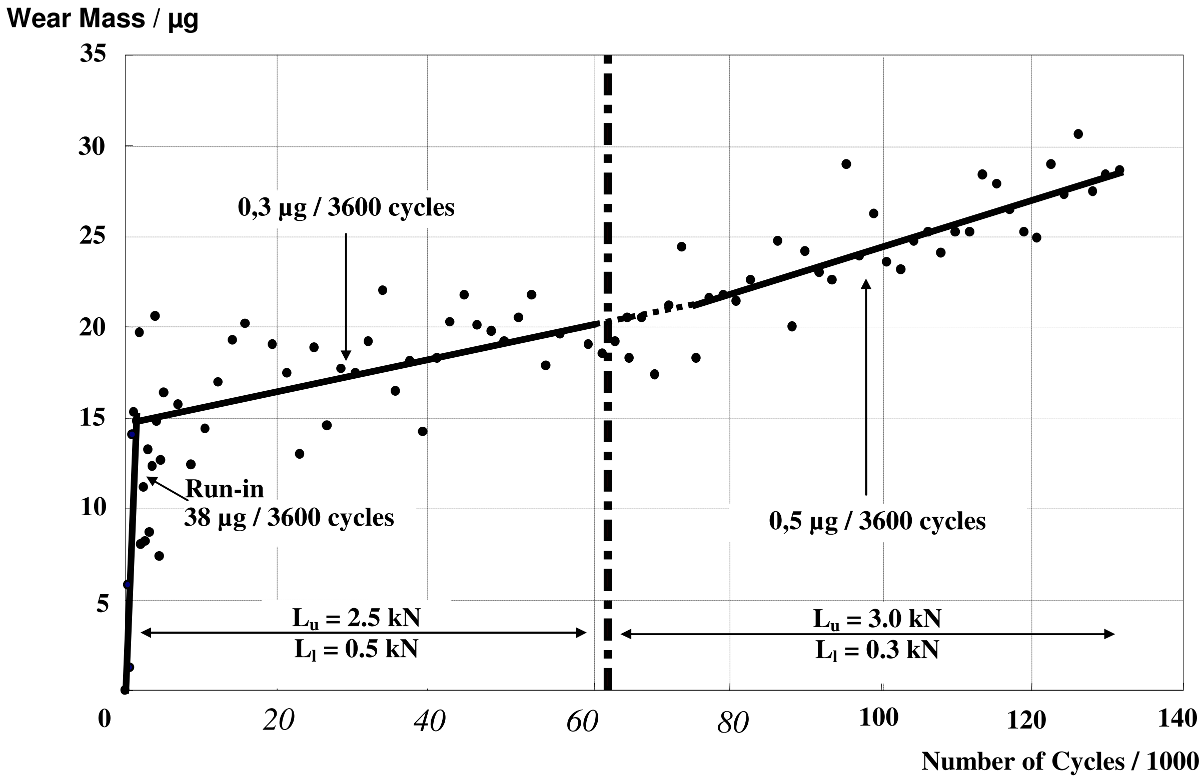

Figure 5: Real time wear measurement of a bone joint prosthesis in a simulator
Material of head and acetabular cup: Al_2O_3; frequency 1 Hz; upper and lower load L_u/L_l in two steps. Raising the load from 2.5/0.5 kN to 3/0.3 kN results an increase of wear rate by 66 %.