Surface Layer Activation Technique for Monitoring and In Situ Wear Measurement of Turbine Components

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Surface layer activation (SLA) is an advanced radionuclide approach for monitoring and measuring material loss due to wear, erosion, and corrosion. In this technique, a minute quantity of radionuclides is induced on the surface of the wearing part. The part is then installed in its normal position or in a test configuration. The gamma ray intensity of this material is monitored externally, in situ, and on-line while the system is functioning under normal operating conditions. The decrease in gamma ray intensity after correction for natural decay half-life results in a direct measure of the wear. The detection system can easily measure a 1% decrease in activity. For a depth of activity of 10 μm, this results in a sensitivity of 0.1 μm or about 10 $\mu g/cm^2$ weight loss. Three recent applications of the SLA technique, two in turbine engines and one in materials testing which is applicable to turbine engines, are presented.

Introduction

RADIONUCLIDES have been widely used for many purposes in medicine, metals, transportation, manufacturing and research. In one of the most economically important industrial applications, surface material is tagged and then followed by the radionuclides which are termed "tracers," acting similar to the medical tracer materials used to measure uptake or metabolism of biologically active chemicals in the body. The alternate function for the radionuclides is to act as "markers" which indicate the amount of material remaining at the location of the original activation. Both approaches require that the debris removed from the surface must be carried away from the original site.

The first application of radioactive tracers as a diagnostic tool in engines was in 1949.[1] In this technique, an entire wearing part such as a piston ring or gear was first exposed to neutrons in a nuclear reactor. This caused the entire volume of the part to become radioactive. The part was then installed and exposed to wear in the operating engine. Detectors placed near the oil line, an oil filter or a sediment trap determined the amount of debris from the part by counting the gamma rays escaping from the debris.

To be accurate, this early tracer technique required an exorbitantly large amount of activity, which created potential safety problems. It was, at least, sufficiently reliable to indicate the onset of wear or sudden changes in the wear rate. An improved version of the radioactive technique based on particle accelerator activation was developed in the early 1970s.[2] Only the material in a thin layer at the surface of the part was activiated, reducing the amount of activity required by three orders of magnitude over neutron activation.

In this improved tracer technique, the detector is placed alone the oil line or oil filter, and the detected activity is dispersed in the oil supply. Consequently, the measurement is affected by the stochastic processes of mixing, settling and chemical reactions. This places limits on the potential accuracy of the technique when used along although its use has been widespread, particularly in locomotives[3] and other diesel engines.[4,5] When combined with a more accurate marker technique, the tracer measurements can indicate wear onset time with remarkable precision.

Received Aug. 6, 1984; revision received Nov. 21, 1985.

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In the early 1970s, Spire Corporation[6,7] in the United States, and the Atomic Energy Research Establishment (AERE, Harwell)[8] in the United Kingdom independently developed an effective marker technique. The basic idea consists of detecting the activity decrease directly from a tinny activated spot instead of detecting the activity increase in the debris. The marker approach gives an accurate measurement of wear quantity while the tracer technique is useful for indicating the onset of wear. By combining the two, the wear can be even more precisely located in time and accurately measured.

Both tracer and marker techniques are separately applicable to several ranges of depths which can be selected by varying the beam energy or species. With *surface* activation, very shallow layers less than 10 μm thick are activated to give the most precise measurements of small wear rates. This precision is most useful in laboratory testing. For example, wear, corrosion, and lubrication effectiveness have been measured in cylinder liners, orthopaedic implants and spark gap electrodes. For these studies, surface activation was used to minimize the time required to produce measurable debris.

Description of the SLA Marker Technique

The conventional marker measurement requires the four steps shown in Fig. 1: 1) Activation of some small volume under the surface of the part which will be subject to wear, and a similar activation of several duplicate parts for test and calibration purposes; 2) an experimental calibration to determine the amount of activity left in the marker spot as a function of the material removed; 3) actual installation of the part and detection of the residual activity as the part is worn or corroded; and 4) analysis of the detection system responses tc determine the actual wear.

In the activation process, the surface of the part is exposed to particles with a precisely known energy from a Van de Graaff accelerator. A few of these particles interact with atomic nuclei in the target material to produce atoms of a desired radionuclide. By carefully choosing the species of both incident particle and energy, a reasonable combination of suitable radionuclide and distribution of activity in the surface of the part can be achieved. A "suitable" nuclide will have a sufficiently long half-life to complete the test and a sufficiently energetic gamma ray to penetrate the engine casing and allow detection from the outside.

A good example reaction is the transmutation of iron-56 to cobalt-56 by energetic protons: $^{56}Fe(p,n)^{56}Co$. In this reaction, the proton effectively replaces a neutron in the target atom so the atomic mass remains 56, but the atomic number increases from 26 to 27. Cobalt-56 then decays with a half-life of 77.7 days and in the process releases gamma rays of several characteristic energies. The most commonly used are gamma rays with energies of .847 and 1.238 MeV.

The amount of induced activity, typically a few microcuries, produces exposure levels around the installed part on the order of natural background. Such a small amount is effective because the detection system only needs to look at the characteristic energy gamma rays emitted by the selected radionuclide. The gamma rays with the same energy produce a peak in the spectrum called a "photopeak," which is easily distinguished from the general background produced by cosmic rays and other nuclides in the environment. Because the activity detected for the wear measurement is concentrated in one spot rather than dispersed in the oil system, the detector can be placed near the spot and effectively "tuned" to detect only one nuclide in the spot. Thus, only a tiny amount of activity is required to produce remarkable accuracy.

Following the calibration of the depth profile, the activiated part or sample can be installed in an operating configuration with a small sodium iodide scintillator counter with a scintillation volume of a few cubic inches mounted in the vicinity of each wearing part. The signals from the detector can then be analyzed using a standard multichannel analyzer (MCA) to store the data. A least square fit computer program is used to extract the area under the peak from the background and the Compton scattering effects.

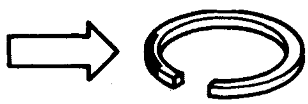
Several possible functional forms are available for this extraction, depending on the shape of the spectrum involved. The most commonly used form is based on the sum of the Gaussian peak and two exponential forms for the background. Alternatively, other Gaussian peaks can be included if the peak of interest has other peaks nearby. These analysis techniques have been proven to be highly reliable for wear measurements in all depth ranges.

Limitations and Value

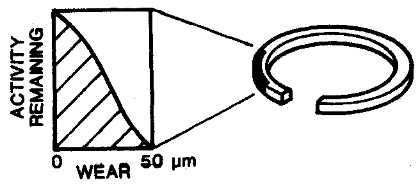
Although surface activation can be applied to virtually any surface which is subject to wear or corrosion and can be placed in the accelerator beam, certain precautions must be observed to preserve the accuracy and meaning of the readings. First, the wear measurements generally represent an average reading over the surface area activated. If the wear is not uniformly distributed, then either a small activated area must be positioned carefully in the area of maximum wear or the activity must be spread out over a large enough area to include all variations, but not so large as to include areas that are not worn. Both require some prior knowledge of the expected wear pattern. This limitation can often be overcome by collimating the detector to observe only a small portion of a relatively large activated area. However, this is usually difficult to do if the activated part is moving deep inside an engine. Some physical access is required.

Another limitation to the technique is that it only measures surface *removal*. Scale, scuffing or other deposits on the surface do not significantly affect the count rate. Consequently, corrosion or corrosive wear can only be easily detected if the material removed is carried away from the surface. The special case of corrosion forming a scale from the activated material can be overcome with precise collimation, but purely external deposits are usually not detectable.

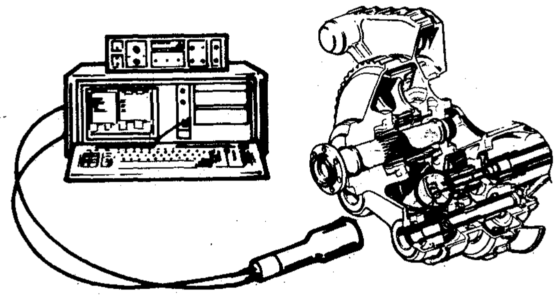
Moving parts do not present any problem for measurement if the motion is cyclic and many cycles occur during the counting period. The brief changes in countrate are averaged out to allow very precise results. Applications in power plant steam turbines, bearings, and other rotating components are currently in progress. However, geometry can still play an important part as it does for stationary parts. If one part of the activated surface is further away or better shielded from the detector, then the average wear measured becomes a "weighted" average with the closer or less shielded areas receiving more weight. Detector positions can sometimes be critical. Roller and ball bearings have been successfully monitored by this technique using small representative spots and circumferential stripes. Rapid rotation insures that variations in the readings are averaged out.



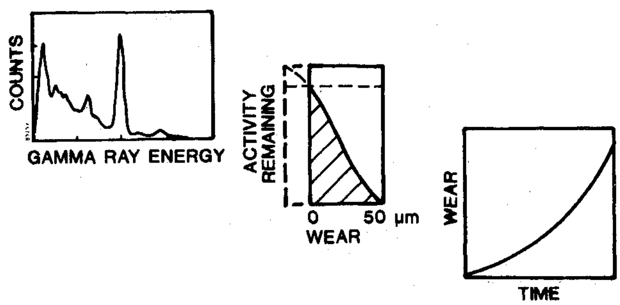
a) Activation of a small volume in the part to be studied and in a calibration sample.



b) Calibration of the activity depth profile by simulating wear.



c) Installation and detection of activity remaining during operation.



d) Analysis of spectra detected to deduce wear.

Fig. 1 Four steps required for the radionuclide marker technique.

Although the selection of the surface area to be activated requires some care, the remainder of the technique is relatively uncomplicated. The activated part is installed using normal procedures, and the detector is mounted near the outside of the system. No changes in the system itself are required. The detector can be damaged by rapid temperature changes, but it is often used in extreme environments with simple insulation and, sometimes, water cooling or heating. Detectors are currently in use near large steam turbine stop valves and cryogenic engines with no degradation in performance.

Although the wear measurements are performed in situ, online, and noninvasively, the activation requires a relatively large accelerator. The part cannot be activated on site but must be sent to the accelerator prior to use. This also means that wear measurements on existing, working parts cannot begin until the part is removed for activation and then returned. For most monitoring applications, this is not a problem since a critical part can be activated when new and prior to a planned installation.

Considering the fact that the SLA marker technique provides wear data when the part is inaccessible and, in many cases, provides information which cannot be obtained any other way, the benefits of the technique far outweigh the costs. For many materials and systems, the cost of each activation is less than $300. Special beam species or large amounts of activity are more expensive. For monitoring applications, the cost of one inspection is often many times the cost of a single activation. For research applications, the extreme precision in determining wear rates allows results to be obtained quickly. The shorter tests save on operating expenses while providing data on the dynamics of wear during the test period. This type of information is not available with conventional techniques.

Virtually any material can be activated to a useful nuclide. This makes the induced activity techniques extremely versatile. The precision possible with the surface layer marker technique, in particular, has made it possible to evaluate the minute differences in wear rates produced by operating conditions, such as temperature or load, coatings or surface treatments, and, particularly, by lubricants or lubricant conditions. The fact that the gamma ray signal readily escapes from an operating engine allows precise wear measurements to be made while the engine is operating, without interruption or interference.

Applications

Three representative application of the SLA process in turbine engines are: 1) the monitoring of a critical engine part in a space vehicle to determine when replacement is required: 2) characterization of wear during various operating conditons of an engine used in an armored ground combat vehicle to pinpoint potentially correctable wear and vibration problems; and 3) simulation and in situ testing of several alternative materials and surface treatments to find which ones work best in the various operating environments.

Monitoring

With the advent of reusable space vehicles, the timely replacement of worn parts in engines and other essential systems is of paramount importance. The extremely high cost of premature replacement and the possible consequences of main engine failure together require that some method for accurately determining the remaining effective lifetime of engine subsystems be used. The technique of SLA is currently being tested as a method for monitoring wear in key engine parts during repeated space flights. Previous testing has indicated that the most critical component subject to wear is the thrust bearing in a turbopump section of the engine. This particular turbopump is driven by a hot-gas turbine which creates additional rotor thrust during start, cutoff and throttling transient operations. The extra axial loading must be absorbed by the thrust bearing.

Other parts, of course, require replacement or preventive maintenance also, but this particular bearing has been determined to require the most frequent replacement of the essential components. If wear monitoring determines that the thrust bearing must be replaced, then the other parts can be inspected or replaced in the same operation.

Preliminary ground testing has supported the feasibility of SLA as an effective wear monitoring technique. In these tests, a narrow band about 1.5 mm wide was activated around the inside of the bearing race where the wearing has been previously observed to occur. The shape of the activated area was controlled by masking around the desired region and rotating the part of the accelerator beam. Both protons and alpha particles were used at several different energies. The worn activated material was carried away by the fuel which acts as a lubricant for the bearings. In subsequent tests, SLA measurements were consistent with other wear measurement techniques and correctly indicated a large increase in wear rate immediately prior to failure.

Testing has shown that one of the most important facets of the SLA technique is that it provides information about the wear rate as well as total wear. Bearings and similar components will typically wear at a greatly increased rate just prior to failure. This allows double criteria for monitoring. Both total wear and wear rate must be below predetermined maximum values to allow reuse of the engine.

Several possible configurations for operational use of SLA are presently being considered prior to final testing. Because of weight considerations, the onboard use of the detector and analyzer is not particulary desirable. The detector and analyzer can simply be used on the ground between flights to determine whether the engine may be safely reused. An alternative plan would be to install a match box size detector with telemetry to allow assessment of wear during flight by an analyzer on the ground. This might provide additional information during an inflight emergency.

A third possible alternative would be to sacrifice much of the energy resolution of the detector and use a Geiger-Muller tube. This would simplify the analysis, but it may not be practical for space applications due to the relatively large and variable background levels above the atmosphere. At the very least, this method would require larger activation levels to insure accurate measurements.

Transient Wear

A wear problem in engines which is difficult to detect is the fact that the wear rate may go up dramatically when engine speed or load changes. This transient wear can even exceed wear at constant high speed and constant loads. Because testing is often designed around fixed speeds and loading or is at least limited to small ranges, these transient wear problems may not be noticed or correctly diagnosed until after prolonged operations.

The combination of marker and tracer techniques can be used to characterize both wear rates and onset of rapid wear for transient conditions. In both of the following examples, the tests have involved turbine engine bearings, but the technique could be applied to any machiney with rapidly moving parts which are suspected of suffering from severe transient wear.

The first step in analyzing transient wear is to confirm that the wear actually occurs during the operational transitional periods. This is achieved using the conventional surface layer marker technique. The depth profile calibrations obtained for 22 MeV alpha particles and 6.3 MeV protons in steels are similar in shape and both extend to about 25 μm. These profiles have been used in preliminary studies to measure wear rates by counting for periods of 10 to 20 min. When a transition period (typcially 5 to 10 s) occurs between two such measurements, the indicated wear corresponds to transient wear rates.

It should be noted that wear rates measured using activation techniques are, in fact, averages of the material removed over

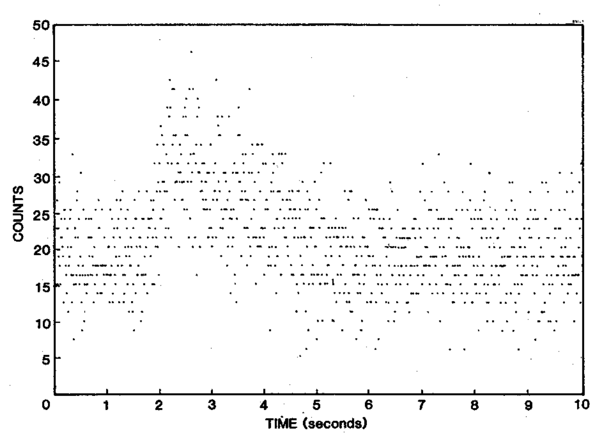


Fig. 2 Counts detected downstream showing the presence of activated debris at about 2.2 s after the transient start time.

the activated surface area. Most types of wear phenomena do not proceed along smooth surface fronts. Ragged or pitted contours are much more commonly observed, particularly when the materials are highly stressed or corrosion is involved. In addition, if the wear occurs only in a highly localized part of the activated surface, erroneous indications can result. The activation should be designed so that wear occurs relatively evenly over the activated area and that this area in fact samples the wear process of interest.

For example, in the gas turbine engine, the transient wear occurs in a separate part of the bearing race from normal wear. Two parallel tracks normally occur, one for constant speed and load and one for transitions. Because the objective in this case is to measure transient wear, the activity was induced in a narrow band along the transient wear track . In the other bearing application, the wear was confined to one track and the activity was centered in that track. In general, the area subject to wear should extend well beyond the activated area boundaries. This allows for slight variations in locations without exposing islands of unworn activity.

Once this marker measurement has confirmed that the wear occurs during transitions, the more elaborate combined tracer-marker technique can be used. There are several reasons why the marker method should not be used alone to provide the exact time of wear onset, although it has previously been used to identify problem speed ranges involved in some transitions.[9] First, the counting rate is generally too low. Because the gamma rays are attenuated as they penetrate the engine casing, marker measurements usually require several minutes to accumulate an adequate spectrum. This is not a problem for most conventional wear processes which occur at low rates over extended periods. To locate a very short but rapid wear process in time requires higher counting rates, so that shorter intervals of measurment can be used.

Another problem with the marker approach for time measurement is that the relative change in counting rate with each increment of wear is small compared with the original counting rate. The change in counting rate for the tracer method can be enormous compared to the original counting rate. Although the absolute size of this change may not be sufficiently precise to quantify the surface material removed, the fact that it is a large relative change makes it a more sensitive indicator for the onset of wear.

To properly calibrate the delay between actual wear onset and registration at the detector, the total amount of activity involved must be measured. This is because the apparent onset delay will vary slightly with the total amount of debris added. The count rate builds at a finite rate which varies with the total amount of activity. This can create the illusion of varying delay times. This is why both marker and tracer measurements must be made together to maximize time resolution.

The sensitivity of the tracer measurement is further enhanced by the expedient of ignoring the energy resolution which is required for the precision of the marker technique. The entire spectrum is summed to produce a much larger net counting rate than any single photopeak could produce. This increase allows millisecond intervals to be studied.

The counting rate is also enhanced by the design of the detector housing. The sensitive 2 in. diam sodium iodide crystal is wrapped in a cylindrical copper coil which is incorporated into the oil line. The copper coil is, in term, surrounded by a layer of lead which performs two functions. First, the lead reduces the background count rate due to cosmic rays and naturally occurring nuclides in the environment. Second, the surface of the lead reflects gamma rays from the oil and recoiling electrons back toward the detector. This adds to the count rate produced by each increment of debris.

A foil backed, thermally insulating layer separates the coil from direct contact with the detector because the gain of the photomultiplier tube is sensitive to temperature changes. The exposed parts of the detector are attached to a water cooled heat sink.

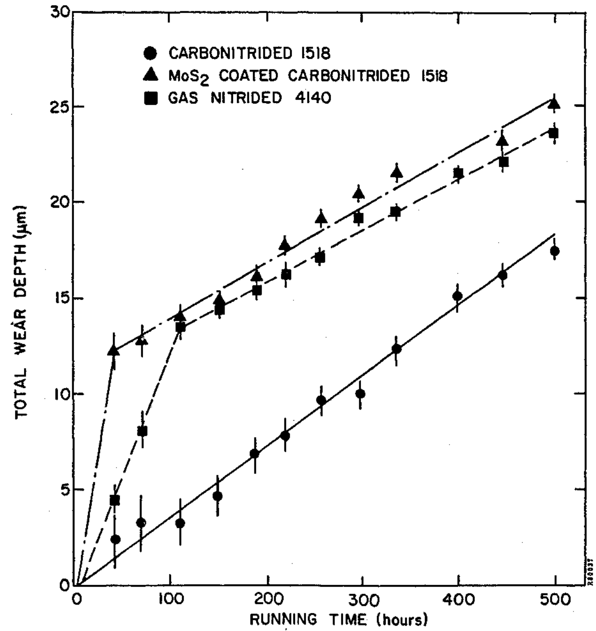


Fig. 3 Material removed in micrometers below the surface as a function of running time in hours. Although the wear rates (slopes) of the two treated materials are less after an initial jump in wear, the total wear over 500 operating hours is still much larger, favoring the untreated surface.

A laboratory mockup of this combined marker-tracer technique has been tested using water instead of oil and traces of manganese-52 from unrelated depth profile calibrations. Actual applications in two engine test cells are scheduled to begin shortly. In the mockup tests, the debris was syphoned with water from a bottle near the "marker" detector which measured the amount of debris removed from the bottle. The water and the debris then passed through the "tracer" detector housing to a recovery bottle for recycling. Figure 2 shows the typical detector responses during one "cycle" or simulated transition.

Material/Treatment Selection

The most common use for the SLA marker technique is to provide immediate feedback on the wear resistance of new materials and surface treatments. In steam turbines operations, for example, a typical turbine part must run for several years in between inspections before the effectiveness of a new material can be examined. By using SLA in either laboratory tests or in situ, the researcher can immediately compare the wear resistance of several materials.

This example involved oil pump gears[10] instead of turbine engine bearings, but the same general idea could be applied to any system with moving parts. Three materials were tested and compared: a carbon nitride SAE 1518 steel, a MoS_2 coated 1518 steel, and a gas nitride SAE 4140 steel. The question was whether the additional processing required to produce the last two steels was offset by a gain in wear resistance. The result of laboratory testing is shown in Fig. 3, which shows the wear depth as a function of running time. The results from the first 500 h of running show that the additional processing degraded the surface wear, and in spite of showing lower wear rates beyond the first 25 h, did not improve the overall total wear. In fact, total wear was increased. As a result, the manufacturer rejected the new processes.

Conclusion

The measurement of wear in mechanical parts using SLA has proven to be a powerful technique for use in laboratory tests, in situ wear monitoring and diagnosis and analysis of system performance. It is a technique which is highly accurate even in situations which are inaccessible to other forms of wear measurement. SLA is ideal for environments which are usually hostile due to temperature, corrosion, ablation, or erosion. The three applications outlined here involved monitoring wear in a critical part to avoid excessive maintenance without compromising operational safety, analysis during transient operations to correct abnormal wear and the screening of materials for wear resistance.

The results of these tests have indicated the superiority of the combined tracer-marker method for timing transient wear onset over either tracers or markers alone. Using markers provides absolute wear measurements for which the tracer techniques is less able, particularly without the energy resolution which must be sacrificed to increase the count rate and improve time resolution. Both the marker and tracer techniques have separately contributed significantly to understanding phenomena such as break-in wear, and steady-state operation wear in engine components. The synthesis of these two techniques promises to produce an additional area for study, namely the precise timing of wear onset for wear which only occurs during brief, transient conditions.

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