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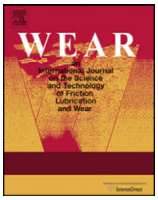

Short communication

TLA and wear quantification of an aluminium–silicon–copper alloy for the car industry

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ABSTRACT

In modern car engines the tribosystem piston ring and cylinder liner is mostly affected due to the latest trends towards high ignition pressure for low fuel consumption, low particle and low CO_2 production, and due to bio-admixtures in fuels. To test the wear behaviour of such a system a model tribometer with realistic loading conditions and a very sensitive and on-line technique has to be used. For reasons of accessibility and applicability only a tracing system with radioactive isotopes turns out to be reasonable. In this paper pieces of an aluminium–silicon alloy cylinder liner were prepared by partial thin layer activation (PTLA). The application of such prepared specimens to a model tribometer tests is shown. The total activity induced is below the free limit by establishing very high sensitiveness at the same time. The tests are carried out in a model tribometer system with piston ring and cylinder liner geometry to investigate the impact of motor oil and diesel fuel as lubricants and different loading conditions on the running in and steady-state wear behaviour of the cylinder liner material.

1. Introduction

Thin layer activation (TLA) has become more and more popular after its first use in the 1970s [1,2] in industrial applications to measure on-line wear and corrosion rates of materials [3,4]. This method uses a beam of accelerated charged particles, such as protons, deuterons or alpha particles, from an accelerator in the MeV energy range onto a metal surface, in which an activated layer of several hundreds micrometers is produced. Wear of this activated layer is measured by means of a radiation detector, such as a scintillation detector or a high-resolution semiconductor detector directly on-line, while the wear process is taking place.

In the last decades, TLA was used intensively to monitor wear and the main focus was put on investigating iron-based materials. Due to the new application of materials, such as aluminium, in the hot spots of the engines, there is a strong demand for sensitive investigations of the wear performance of these materials in the corresponding harsh tribological conditions. In this work model tribometer tests are performed for which partial thin layer activation (PTLA) is applied as part of the on-line wear measurement of an aluminium alloy that is used in the automotive industry as material for the motor block as well as cylinder liner surface. Partial TLA refers to the fact that only a fraction of the specimens' surface was activated.

2. Material

Aluminium–silicon alloys have become very important as basic material for engine blocks due to their favourable mass-to-performance ratio, high thermal conductivity, good corrosion and wear behaviour. The material's high wear resistance is a direct result of the hard silicon precipitations within the aluminium matrix that brings a reinforcing effect [5]. In this paper pieces of an aluminium–silicon–copper hypereutectic alloy, which is used in state of the art car engines, are studied.

An average composition was obtained by an X-ray fluorescence spectroscopy (XRF) that was made on the bulk material and on the cylinder liners' surface to check the amount of the main elements (aluminium, silicon and copper) in the first micrometers of the surface.

Aluminium and silicon are the dominant components and together they reach approximately 94% in mass (aluminium 76% and silicon 18%); copper is present in the range of 3.5–4.5% in the mass. Other elements such as Mg, Fe, Mn, Zn, Ti can be found in traces between 0.2% and 0.5% in the bulk. It is also believed that the copper distribution is homogenous on a macroscopic scale.

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Nomenclature

$^{nat}A(c,d) \rightarrow {}^{xx}B$ The natural element ‘A’ irradiated with a beam of particles ‘c’, will undergo a nuclear reaction with emission of particles ‘d’ and will be transformed in the isotope of atomic mass ‘xx’ of the element ‘B’

3. Thin layer activation procedure

The used 20 MeV cyclotron [6] is capable of accelerating protons (p), deuterons (d), 3He and 4He (alpha) particles with variable energy and intensity. To choose the appropriate target nuclear reaction for activation purposes of an alloy is a very sophisticating task. Different parameters have to be taken into consideration as discussed by Ditrói [7] or Fehsenfeld et al. [8]:

1. Element(s) or material to be activated (cross-section) as wear indicator.
2. Technical characteristics of particle accelerator (energy of charged particles, beam diameter, intensity, etc.).
3. Cost of the activation (time and money) for a given target reaction and given required activity.
4. Characteristics of the resulting radio-isotope (half-life, free handling limit, gamma lines and intensity, etc.).
5. Bulk material characteristics especially the tribological performance must not be changed due to the activation (beam intensity, cooling system, etc.).

All nuclear reactions on aluminium and silicon have to be taken into account, but only a few product isotopes of these reactions are suitable for tribological applications due to their properties (Table 1).

Because of the restrictions for nuclear reactions with the aluminium or silicon phase in the alloy (Table 1), it was decided to target copper, which is present in the amount of approximately 4% in mass in the bulk material. Copper is well suited for a nuclear reaction with protons to produce Zinc 65 (^{65}Zn) and has perfect half-life for wear tests (Table 2).

To fix the parameters for irradiation, a simulation followed by a calculation of resulting activity is done by the help of nucleon stopping ranges in materials based on tables by Ziegler [9].

The irradiation energy – impact energy of the charged particles – on the target corresponds to the maximum of the cross-section of ^{nat}Cu(p,x) → ^{65}Zn reaction [10]. This choice reduces the irradiation time to a minimum. The beam intensity was set to a moderate level of a few microamperes to prevent any changes in the material’s surface properties and structure due to heating. Irradiation time was calculated considering an optimum activity below the free limit [11] for all pieces of cylinder liners.

For a high-resolution wear measurement the majority of produced radioactive isotopes should be found in the very first layers that are of interest for the tribological investigations. Hence the penetration depth of the charged particles perpendicular to the surface has to be minimized. This can be achieved by adjusting the irradiation angle from normal to grazing inclination (Table 3). Angles lower than 10° are not used commonly because of possible scattering and reflection effects of the projectiles when hitting the target surface. These effects would severely affect the calculated depth profile.

Two pieces (Table 3: A1, A2) were irradiated under 90° – cyclotron beam perpendicular to the surface – producing a rounded spot. The other three pieces (Table 3: A3, A4, A5) were irradiated under a 15° angle producing an activated strip instead of a spot.

Table 1
Extract of possible nuclear reactions on Al or Si and their restrictions.

Target reaction	Restrictions
^{nat}Al(3He,x) → ^{22}Na	High cost of Helium3 and higher difficulty in tuning the beam
^{nat}Al(p,x) → ^{22}Na	Threshold energy 25 MeV
^{nat}Si(d,x) → ^{24}Na	Too short half-life (14,95 h) for industrial application and very low cross-section
^{nat}Si(p,x) → ^{22}Na	Threshold energy around 30 MeV

Table 2
Nuclear reaction used for irradiating the cylinder liner material.

Target reaction	^{nat}Cu(p,x) → ^{65}Zn
Threshold energy	2.20 MeV
Max cross-section	220 mbarns at 10.5 Mev
Half life of ^{65}Zn	244.26 days
Gamma lines of ^{65}Zn	1115.55 KeV (unique)
Free handling limit of ^{65}Zn	1 MBq

After irradiation, the activity of the samples and the produced isotopes were checked using a high purity Germanium detector and compared with the calculated values. Additional isotopes, such as ^{56}Co, ^{52}Mn, ^{48}V, ^{51}Cr, and ^{22}Na, with short half-life or with negligible activity were produced during the irradiation. The elements, that are present in the alloy in traces, have also been activated. All these isotopes do not have gamma lines that can interfere with the ^{65}Zn energy line in the wear calculation. Anyway, the activity from ^{65}Zn is orders of magnitude higher than the activity of all other isotopes produced.

In addition to copper, also iron could have been used for the activation. Depending on the material of the specimen, the best suitable element should be chosen for wear investigation. In the aluminium–silicon alloy the copper concentration is much higher than that of iron. The activation of iron is often used for measurement of the wear performance of grey cast iron, which is used as cylinder liner material in internal combustion engines or hard working steel for, e.g. piston rings. Parameters and radioisotopes obtained by activation of iron differ from the previous case and are reported in Table 4.

4. Principles of wear measurement with radioisotopes

Radiation detection belongs to the most sensitive measuring techniques for concentration, as the decay of each single radioactive isotope can be recorded. Consequently, the methods using tracing isotopes are also used for high sensitive and on-line measurement of wear. During the test run in a model tribometer [12] wear particles of the doped and stressed specimen are transported to a radiation detector by an ambient medium, in many cases by the lubricating oil (Fig. 1). The measured activity in the ambient medium is therefore the indicator for the quantity of wear of the specimen. This concept is dependent on the mathematical correlation of three factors: the activity in the lubricant, the depth profile of these radioisotopes in the specimen and the conversion into a tribological parameter, such as wear rate. This coherence is the key to this measuring technique [13].

The activity in the oil is a result of wear volume and concentration of isotopes in the wear zone of the specimen. The concentration of isotopes in the specimen is dependent on a lot of parameters of activation, especially concerning thin layer activation of a few microns. This non-linear concentration of isotopes perpendicular to the surface (=depth profile) has to be well known for wear measurement, particularly for highly sensitive wear measurements.

Radioactivity in general must be treated with duly care. The total activity of the specimens used for the investigations in this paper is