Non Destructive Evaluation and Modelling of Structural Materials Durability in relation with Maintenology Concerns at INSA Lyon

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Abstract
Two aspects of maintenology concerns relating to materials science in a French technical university as INSA Lyon are addressed: a first one about modelling the life distribution of mechanical components manufactured from high strength steel; the second one about the development and interpretation of Barkhausen noise measurements, an original non-destructive evaluation method for the integrity of stainless steel used in nuclear power plants.

Keywords: materials durability, micromechanical models, steel cleanliness, Barkhausen noise, fatigue.

Introduction

There is no such society as the Japan society of maintenology in France. This means that beyond state-regulated fields such as nuclear or civil aviation safety, there is no general scheme for optimizing maintenance in order to avoid downtime and failure on the one hand, and also too early replacement of components on the other hand. Yet some aspects of the problem are being addressed by specific scientific societies. For instance :

- standard proposals or updates for fracture of aeronautic components or roller bearings are being discussed within the European Structural Integrity Society (ESIS), which gathers industrial and academic partners for regular discussions ;
- reliable design rules against fatigue are being adressed by the Fatigue commission of the French Metals and Materials Society (SF2M), in presence of academics, materials and assembling industries, certification companies.

Large companies have research and development departments that distribute the scientific and technological issues to targeted academic cooperations and integrate the results with respect to component reliability themselves. They can also cooperate with a specific academic institution (French Institute of Advanced Mechanics, IFMA [1]) that has developed tools for stochastic structural design, failure origin probability, etc.

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For smaller companies, a long-term cooperation with an academic research institute can result in a dedicated model development, where the academic part also analyses the reliability of the component.

On the academic side, maintenology requires inputs from all engineering sciences : mechanics, materials, thermics, chemistry, assembling technologies, computing... In France, such a knowledge is found in technical universities or engineering schools. INSA Lyon (5000 students) is an original intermediate model between a small-sized engineering school, usually very specialized, and a broad-range technical university. Since its creation in 1957, it has applied its scientific assets to solve industrial problems under joint research. Its research is organized in laboratories ; MATEIS is the Structural Materials Engineering and Science lab of INSA Lyon.

Our purpose is to illustrate the scientific and technological aspects of academic / industry cooperations involving maintenology on the basis of two examples :

- a case related to medium-sized companies (steelmaker and manufacturer) where a long-term cooperation (20 years, 8 PhD theses) has lead to a stochastic model with physical bases that describes the failure time of a population of roller bearings in relation with steel cleanliness and bearing dimensions ;
- a case where a tool for fundamental studies (mobility of Bloch walls in pure iron under applied magnetic field) has been continuously improved and dedicated so as to evaluate

the integrity of steel structures in various fields including nuclear power plants : the Barkhausen noise.
The physical bases of the models that have been published elsewhere will be outlined. Some emphasis will also be laid on the way how the research has been developed.

Roller bearing fatigue

The steel track on which balls are rolling can fail by fatigue. In one mechanism, namely subsurface initiated deep spalling, cracks are initiated from subsurface inclusions and grow towards the track surface. The current approved standards rely on a model by Ioannides and Harris [2], using an empirical correlation between applied load, bearing geometry and the time at which 10 % of the bearing population has failed during trials.
From the middle of the 1980s to 2000, MATEIS contracted research with at first the bearing manufacturer SNR Roulements (France), then the steelmaker company Ascometal and the end user in aeronautics SNECMA, and occasionally more partners within European contracts. The basic laboratory competences supplied were :
- fundamental competences in cyclic strain of metals (elastoplastic transition, description of cycles, cyclic dislocation storage) and micromechanics (Eshelby model around an inclusion)
- metallography, statistical evaluation of populations of inclusions
- ultrasonic detection of cracks.

They were extended by cooperation with the Solid and Contact Mechanics Lab (LAMCOS) at INSA for the description of ball/track contact in complex situations, such as for a dented track surface [3].

A model was gradually built, incorporating the results of many PhD theses. The analytical description of the elastic Hertzian contact between the ball and a flat track provided the stress field in the solid below the track. Such a geometry generates a maximum von Mises stress at a depth below the surface about one half of the radius of the ball / track contact area. This is the zone where steel cleanliness matters.
The deterministic model considers the stress concentration around a spherical inclusion that arises from the difference in elastic constants between matrix and inclusion. The effect is all the more enhanced as the difference in Young's modulus is large, leading to pronounced effects of alumina inclusions.. The stress concentration factor is as large as 3, leading to plastic straining of the matrix around the inclusion.
The local stress conditions then lead to cyclic dislocation storage in a volume that can be visualized by metallography : the white etching area, looking like butterfly wings around the inclusion.

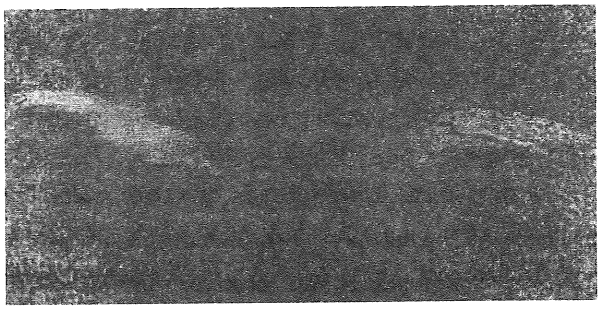

Fig. 1 butterfly around an inclusion (approx size 30 μm).

When the dislocation density inside the previous volume results in local stresses exceeding the cleavage limit, a crack is formed, approximately of the size of the inclusion. Then the crack extends towards the track surface according to a Paris law, with decreasing efficiency since ΔK decreases due to both friction between crack lips (this is mode II crack growth) and crack geometry (the length of the crack increases, not its width).
As a matter of fact, the deterministic model is able to predict whether an inclusion of a given size at a given position will induce subsurface-initiated deep spalling under a given contact pressure (i.e. the generation of a crack on an inclusion and its growth up to the surface) and how many cycles are necessary to fail the washer bearing. It is also able to state which inclusions (size, position) are harmful under a given applied load, and eventually to give a load limit under which no crack is going to nucleate whatever the position of inclusions. This is the concept of safe operation limit.

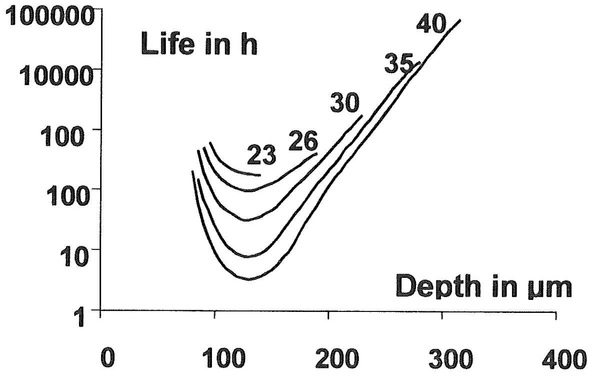

Fig. 2: effect of position and inclusion diameter on the total fatigue life for spherical alumina inclusions with diameters expressed in µm (1000 h = 675.10^6 cycles) [4]

In order to consider the distribution of fatigue lives of a population of bearings, a statistical model has also been developed, that relies on the observed distribution of inclusion diameters. A Monte-Carlo processor generates random inclusion sizes and positions in the volume of a bearing (flat washer) until the inclusion volume fraction is reached. Then the model runs and determines the fatigue life of the simulated bearing.. Repeating the process many times for a series of bearings, a distribution of fatigue lives can be described, that is consistent with experiments.

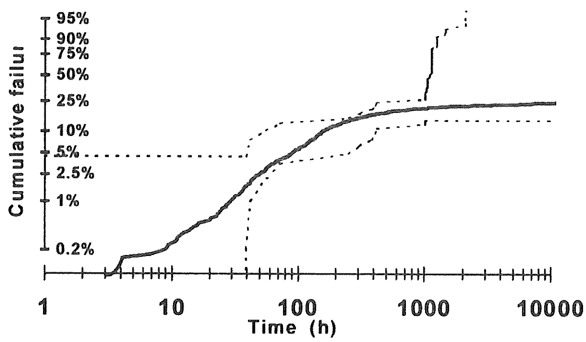

Fig. 3 : simulated distribution of fatigue lives of a population of bearings (flat washers). Dotted lines represent excess and default estimates from experiments. Note that more than 50 % of the samples will never fail by the studied fatigue mechanism.

The distribution of fatigue lives depends strongly on the inclusion size distribution [4]. It is thus important to detect the large inclusions and estimate their proportion. In Japan, Y. Murakami [5, 6] has developed a method based on the Gumbel statistics of extremes, that relies on the largest inclusion sizes detected on 40 metallographic observations. The graph between -ln(-ln(G)) and the particule size, G being the distribution function of sizes, should be a straight line. This works well for exponential size distributions, but proves non-conservative for the log-normal distribution such as the one used to simulate Fig. 3 and 4.

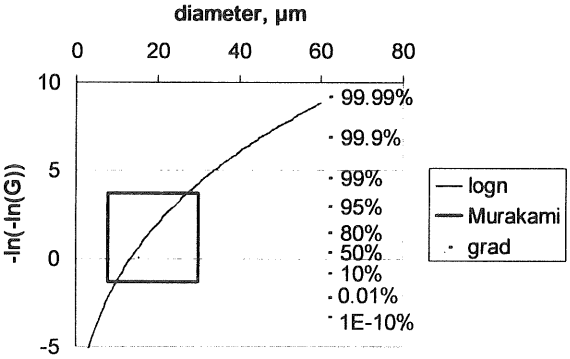

Fig. 4 : Gumbel graph for the statistics of extremes using a lognormal distribution of diameters with mean 1.1 µm, deviation 0.76, 2140 inclusions / mm^3. The box is the area experimentally accessible to the Murakami method, from which a linear regression on 40 values of the maximum size would be made.

The British researchers G. Shi and H. Atkinson [7, 8] challenge the method by proposing to rely on 800 particles on the tail of distribution, considering Generalized Pareto Distributions. These are derived from the exponential distribution but some can derive an upper bound for the maximum size, whereas both the exponential, normal and lognormal distributions have no upper bound.

Our experience shows that the Murakami method is quick and very efficient in order to rank materials. Yet for implementation of the inclusion size distribution in our roller bearing model, extensive metallography investigations of the population of inclusions are necessary, and even a back-up by an additional 3D method with ultrasounds or X-ray is vital to assess the largest particle sizes.

Our model is now used by steel manufacturers and bearing manufacturers in order to determine the defect rate of a given steel quality and also the degree of cleanliness able to comply with new high quality requirements. Current research includes the effect of non-circular inclusions and clusters of inclusions [9].

Barkhausen noise

When a magnetic field is applied to a ferromagnetic material, the magnetic domains reorganise, leading to the movement of the Bloch walls. However, the walls are pinned by defects, leading to a jerky movement similar to that of dislocations gliding on a plane with obstacles. So, when a simple low-frequency triangular magnetic field is applied, the total magnetic field does not follow smoothly the magnetization curve but undergoes small high-frequency fluctuations called Barkhausen noise.

This noise was first studied at INSA by Pr. A. Vannes, who conducted simultaneously academic research on pure Fe or Ni and applied research in order to monitor damage [10]. It was then used in a research team devoted to fatigue ; they noticed that the shape of the Barkhausen signal recorded during cyclic straining of the carbon steel A42 strongly depended on the position on the cyclic curve and inferred that it would be able to monitor internal stresses [11]. Four further PhD theses adressed both fundamental (the role of alloying elements on the signal, comparing pure iron to very low carbon iron) and practical non-destructive evaluation issues in relation with the French Mechanics Industry Technical Centre (CETIM), the steelmaker Arcelor... A breakthrough was realized during a PhD thesis with the French electricity supplier EDF [12]. This work is briefly described in the following paragraphs.

The experimental device built by INSA consists in an excitation magnetic circuit that generates a triangular applied field at low frequency (between 10^{-2} and 1 Hz) in the specimen. A Hall-effect detector measures the resulting field outside the sample. The Barkhausen noise is detected using a surrounding coil located in the useful part of the specimen. The high frequency components of the signal (above 10^{+3} Hz) corresponding to the Barkhausen noise are selected through a high pass filter.. The root mean square value of the noise is then computed and analysed.

The device was adapted to a tensile machine, so that the Barkhausen noise can be recorded between straining steps, notably at any position along a cyclic stress-strain curve.

The signal interpretation depends on the steel microstructure that offers strong or weak obstacles to the motion of the Bloch walls. Each magnetic constituent of steel has its own signature (for instance, the field at which the Barkhausen noise is maximum). Comparing signatures, it is then possible to follow modification of constituents during straining or thermal treatment.

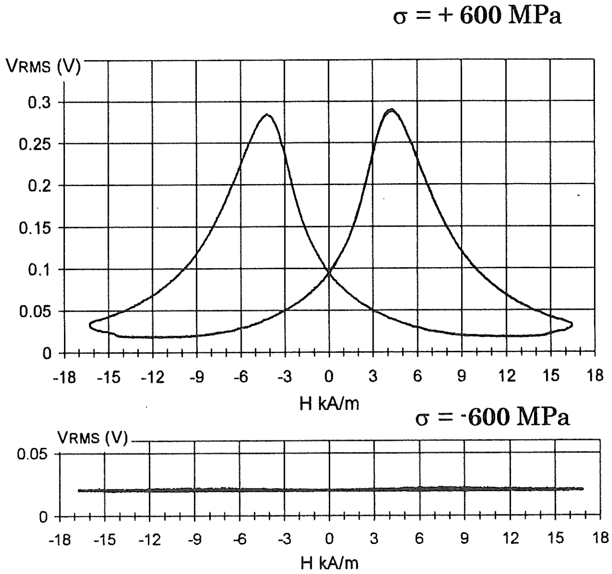

Fig. 5: Barkhausen root mean square (RMS) signal as a function of the applied magnetic field H obtained at highest and lowest stresses of a stabilised fatigue cycle (N = 600) for a cold rolled 304L steel cycled at ε_a = +/- 0,8%.

As an example, the austenitic stainless steel grade 304 L is the base material for the primary circuit in French nuclear powerplants. The austenite is not the equilibrium phase at the temperature of use and furthermore at room temperature. It can be destabilized and turned into martensite by cyclic straining. The Barkhausen noise proved to be sensitive enough to detect a slight modification of austenite : the transformation of as low a volume fraction as 2.5 % into martensite [12].

Furthermore, a large difference in signal appears between a fatigue test interrupted in tension and the same interrupted in compression: Fig. 5. The Barkhausen activity is lowest in compression while highest in tension.
This phenomenon cannot be interpreted in terms of applied stress or strain, as shown in Fig. 6 where the area under half of the Barkhausen curve ARMS is plotted at different points of the stress-strain curve.

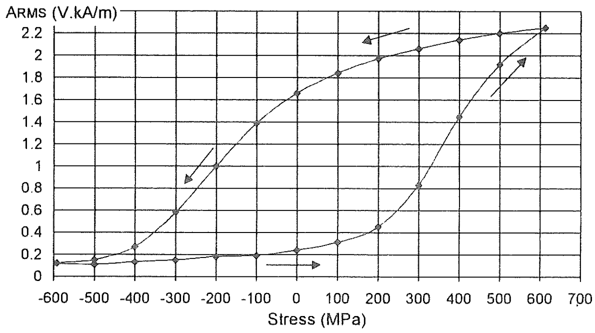

Fig. 6 : Variation of A_{RMS} = f(σ) along a complete stress-strain loop : cold rolled 304L steel ; ε_a = +/- 0,8% ; N = 600.

On the other hand, a unique variable was shown to describe the above curve: the internal stress inside the martensite, determined using the embedded inclusion approach. As a matter of fact, an isolated martensite island surrounded by non-transformed austenite can be approximated by an elastic inclusion surrounded by a much softer matrix with about the same elastic constants, which deforms plastically under low-cycle fatigue tests. In such a case, the internal stresses inside the lathe can be described by the Eshelby method. Assuming a spherical lathe shape since we had no information about a preferred lathe orientation, it was then proved that a univocal master curves links the Barkhausen noise to the internal stress inside the martensite inclusion, Fig. 7.

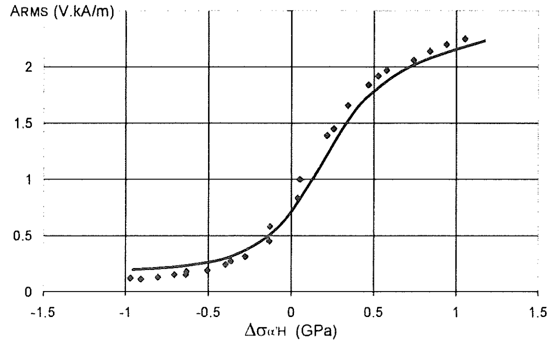

Fig. 7 : A_{RMS} vs internal stress (within α'-martensite) change along a stress-strain loop : cold rolled : ε_a = +/- 0,8% ; N = 600.

This example proves that the Barkhausen noise can be a powerful tool to monitor separately variations in the constituents of a material. But a good knowledge of the pinning defects and of the microstructure is required for a safe interpretation of the results.
Current areas of development are the improvement of the technique as a non destructive inspection method, linked with the understanding of the relation of the signal with the microstructure. Our lab participates to the universal network for magnetic non destructive evaluation initiated by Iwate University in Japan [13].

Other fields for maintenology

MATEIS is also active in the non destructive instrumentation of structures that can be affected by mechanical damage, aggressions from chemical environment or a combination of both. The Polymers Group studies the damage of polymers with nano-scale reinforcements under irradiation. The Ceramics and Composites Group examines the growth of cracks under static load at high temperatures in various ceramic microstructures. The Durability and Smart Materials Group studies creep of fibre-reinforced composites and aims to predict the remaining life of each individual instrumented sample. The Corrosion Group detects as early as possible stress corrosion precursors. The last three teams use acoustic emission as a reference tool for damage dectection, and combine it with other macroscopic global techniques on the one hand, microstructural characterization of defects on the other hand, so as to assess one signal type to one damage mechanism whenever possible.

Other non-destructive techniques include Thermoelectric Power and Eddy Currents for metals, Ultrasounds for other materials.

Conclusion

The durability of structural materials is a societal concern and a major research theme in an engineering school and its structural materials research laboratory. The initiative of finding promising new fields of applications belongs to the university researchers, but scientific and economic value is added when industry partners invest in academic-industry cooperation through PhD theses notably. It is all the more profitable to both parties as the research effort is carried out on a long term basis.

International cooperations also were useful in both the illustrations shown here. The roller bearing research got a great thrust through a European project, that enabled stimulating exchanges with German and Swedish teams developing models on a more empirical basis. The conferences on bearing steel technology regularly organised by the American Society for Testing and Materials are also open places for critics and discussion. As for the Barkhausen noise, it also was included in a European round robin project that compared the predictive potential of various non destructive techniques on steels for the nuclear industry.

It is therefore hoped that the present lecture will provide opportunities for cooperation with Japanese scientists and engineers in our field of research.

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