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# Determination of Metallic Fatigue in Nitrided Steel using a MDK Magnetic Nondestructive Tester

**Akiyoshi ONUKI**
**Yamagata University (Formerly)**
**1-3-73 Josei, Yonezawa-shi, YAMAGATA 992-0054, JAPAN**
**Tel&FAX:+81-(0)238-5194**
**E-mail: onuki_ja2007@yahoo.co.jp**

**Hiroaki KOHAMA**
**Kaisei Engineer Co. LTD, Sone Bldg, 1-3-2 Nishi-tsuruma,**
**Yamato-shi, KANAGAWA 242-0005, JAPAN**
**Tel:+81-(0)46-276-6664, FAX:+81-(0)46-276-5196**
**E-mail: kaisei_eng_co@pop07.odn.ne.jp, URL:http//www.odn.ne.jp/~kaisei/**

**Abstract**

In many cases of the structural fracture, it is supposed that metallic fatigue is one of the important reasons. Many researchers have revealed the fatigue process on the surface of metals. But, in surface hardened steel, internal cracks develop slowly larger before the fracture. So it is needed to detect small inner defects in the machine parts or the working structures, non-destructively. In this paper, a new magnetic sensor (MDK sensor) was used to determine the fatigue process of the nitrided steel (in a surface hardened cylindrical specimen). As experimental results, the small fatigue damage is found out in the midst stage of the fatigue life. This new sensor was supposed to be available to determine the inner defect of metals, as one of NDT methods.

Keywords: Metallic fatigue, Nondestructive test, Magnetic detector, MDK sensor, Gas nitriding, Rotating bending fatigue.

## 1. Introduction

Safety of the structures and machines is the essential requirement in the complicated society, in which the higher level of technique and technology is demanded. For a long time, the machine has been supported by many designers and manufacturers in material technology. Vast historical research data on the failure and fracture of the machine and structure are stored.

Recently many kinds of accidents, such as the failure from a wheel hub part of the traffic vehicle, remind the responsibility to researchers and engineers concerning the machine. In the long history of the metallic fatigue research, a lot of important evident has been clarified, e.g. the relationship between the life and the surface crack growth, the fracture toughness of artificial notched material and the endurance life. Fracture mechanics and related area has contributed to design and maintenance of machine and structure. Although technology of the inspection of defects and the deterioration of materials is developed, most non-destructive inspection equipments or detectors are working for the surface of test pieces, but they have been limited caused by shapes and/or conditions. It was very difficult to find inner cracks by other techniques as X-ray or ultrasonic instruments. There are a few studies on such inner cracks using the magnetic detector. It has been thought that magnetic detectors could not be able to apply for inner defects for a long time.

In this research, one of the electro-inductive typed magnetic sensor, MDK MAGNETIC Sensor, was applied for the detection of the fatigue process of a surface hardened steel, and revealed the possibility to inspect the position of fatigued part or the uniformity of hardening, and life stage of the fatigue process. To improve the fatigue strength or the surface hardness, surface hardening treatments are very effective. Authors have performed the research on the fatigue of a nitrided steel, which has the high fatigue strength because of the hard surface layer and the residual stress [2]. The experiment was done for the fatigue life by means of a rotating-bending fatigue machine, attached with a MDK sensor during fatigue. The fracture surface was observed using a SEM. In this paper, the validity of this method is discussed, and the availability of the instrument is shown.

## 2. Background of this research

Non-destructive testing has been developed for many measurement of change in material state. The technical field of applications of nondestructive materials characterization, particularly quantitative, characterization of surface, near-surface, and bulk material condition for flat and curved parts or components using magnetic field based or eddy-current sensors is reported in a US Patent document [1].

Ordinarily the eddy-current sensor is used to detect the surface defect or crack such as welding flaw, but it is limited within the surface layer.

The fatigue strength and life of an ion-nitrided steel has been investigated by authors [2], and also the effect of hardened surface layer was studied by other researchers [3]. But it is difficult to determine the inner defects like micro plastic zone or small crack beneath the surface hard layer, which suffered fatigue load after nitriding treatment. In such materials, surface damages could not be found before the fatal fracture, essentially.

There are many methods and equipments for the non-destructive inspection for faults in materials. The main testing method of magnetic non-destructive techniques is the Eddy current testing, although, it is not available to search inner defects beneath the surface in metals.

As a kind of magnetic detectors, a MDK magnetic sensor can apply to get the information from inside the materials. In this paper, an experiment has performed to reveal the level and location of the defect during the fatigue test. And the prediction of the life span of fatigue can be made by means of reference data of fatigue.

## 3. Principle of MDK Magnetic Sensor

Magnetic properties of materials are associated with magnetic permeability, electric resistance and conductivity, and should be controlled by the change of microscopic structure of material such as plastic deformation, fatigue damage and other micro cracks under loading. MDK Magnetic Sensor (which means Magnetic Detector of Kaisei Corporation, JAPAN), which is a kind of magnetic detectors, is a sensing system which has two coils; the primary coil causes alternative current (reference signal) to penetrate into the specimen and the secondary (receiver) coil can detect the change of the amplitude and the phase delay caused by dislocation tangles or small defects at the grain boundary. This output is affected by experimental conditions such as the lift (which means the distance from the surface of the object to the sensor), applied voltage, temperature, frequency wave and other conditions. More details and applications of MDK Sensor are introduced in the supplement at the end of this paper.

## 4. Experimental procedure

The material used in this research is one of tool steels, HPM31 (Hitachi Metal Co.Ltd, Japan), which belongs to a kind of hardend special steels for the plastic molding. Specimens are machined in the shape and dimension, which has R-shape part given a stress concentration factor K=1.01, as shown in Figure 1. The chemical compositions of material are shown in Tables 1. After machining, the specimens were annealed to remove the residual stresses at 600 degree centigrade for 1 hour in vacuum. And the nitrizing treatment was given as the gas soft-nitriding under the conditions shown in Table 2. To improve the fatigue strength or surface hardness, there are some effective methods like surface modifying treatments, including gas nitriding, ion-nitriding and other case hardening.

The fatigue tests were performed using a rotating-bending fatigue machine (Ono-type Fatigue Tester, H-6, made by Shimadzu Co. Ltd), under 3000 r.p.m., attached with an electro-magnetic detector, MDK Sensor, holding the same distance from the specimen surface. To compare the of nitriding, the same experiment has be done for non-nitrided specimens.

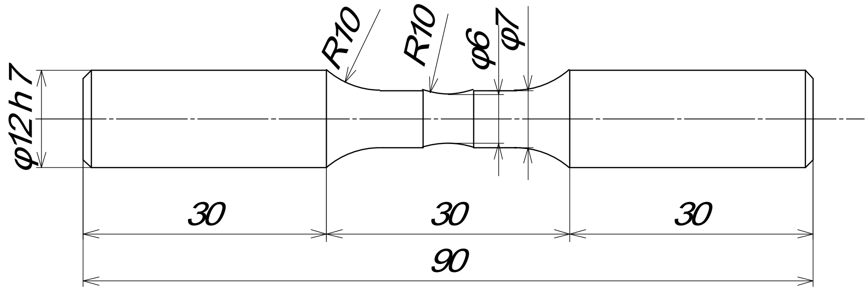


Fig.1 Shape and Dimension of Specimen

Table 1 Chemical Compositions of Material (wt.%)

| C | Si | Mn | P | S | Ni | Cr | Mo | V |
|---|---|---|---|---|---|---|---|---|
| 0.7 | 1.0 | 0.5 | 0.025 | 0.01 | 1.3 | 8.0 | 1.3 | 0.9 |

Table 2 Condition of Gas Soft Nitriding

| Gas Contents | Temperature | Vacuum | Holding Time | Cooling |
|---|---|---|---|---|
| $NH_3$:$CO_2$,:$N_2$ | 520℃ | 500Pa | 3hrs | In Furnace |

## 5. **Experimental results and Discussions**

The hardness distribution from the surface to the center of the specimen is shown in Figure 2. A SEM micrograph of the fatigue fracture surface of the nitrided specimen is shown in Figure 3. In the gas-nitrided specimen, the hardness shows maximum value just beneath the thin surface layer, and rapidly decreases toward the center of the specimen. And the fatigue crack is observed at over 300 micron meter depth beneath this hardened layer. The typical flat round crack so called "fish-eye" was found at the area. It suggests the difficulty of detecting the inner crack.

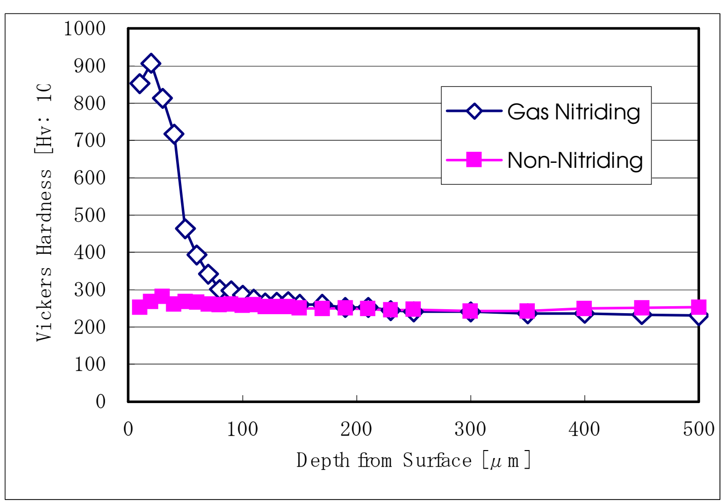


Fig. 2 Hardness of Gas Nitrided Steel (Hv: in Vickers Hardness Number)

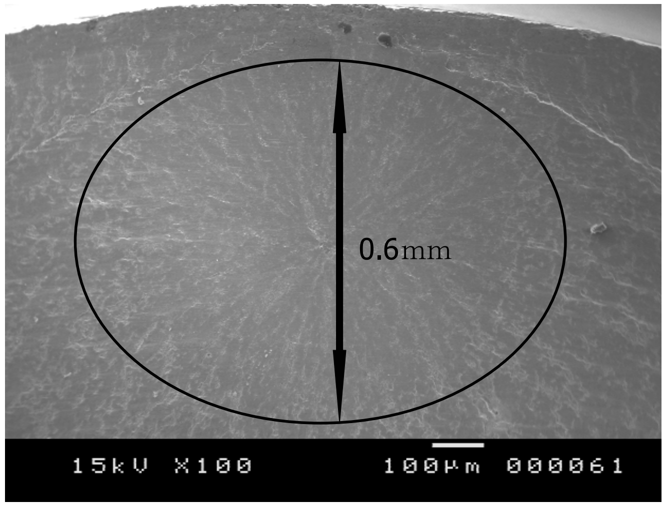


Figure 3　SEM micrograph of fatigue fracture surface of nitrided specimen

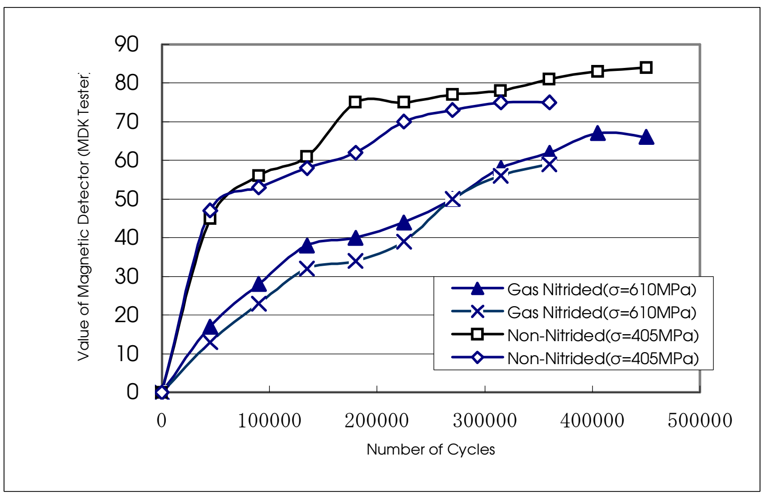


Fig.4　Variation of MDK Value according to Life Cycle

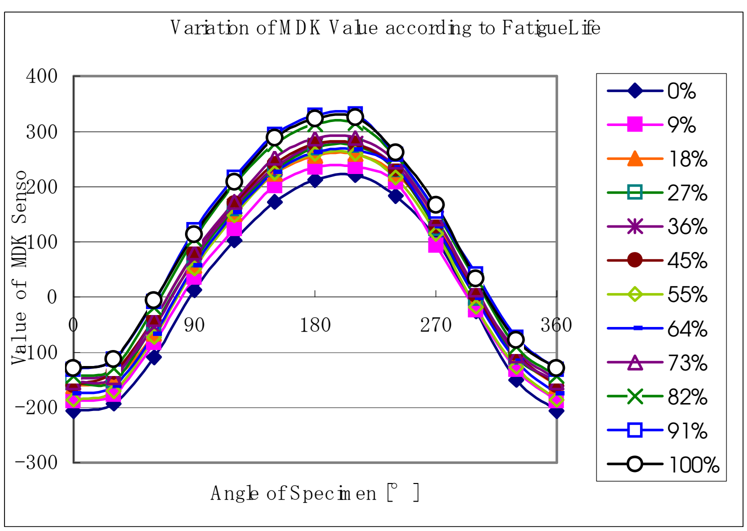


Fig.5　Variation of MDK Value according to Life Cycle
(in Sectional Angle)　[ σ ＝610Mpa，Nf=450000]

From the S-N curve of the rotating-bending fatigue test for the gas-nitrided specimen, although the fatigue strength is 340 MPa for the non-nitrided specimen, it is improved to 550 MPa by the gas-nitrizing, as shown in Figure 4. To determine the effect of the fatigue process, the MDK value was continuously measured under the same repeated stress at same intervals to the fatigue failure. The change of MDK value shows a gradual growth in every loading condition in Figure 5.

The experimental result of the nitrided specimen has shown the uneven distribution of MDK test values around the surface measured by rotating each 30 degree, as shown in Figure 6. In this figure, each point was plotted as the ratio of the fatigue life of the specimen.

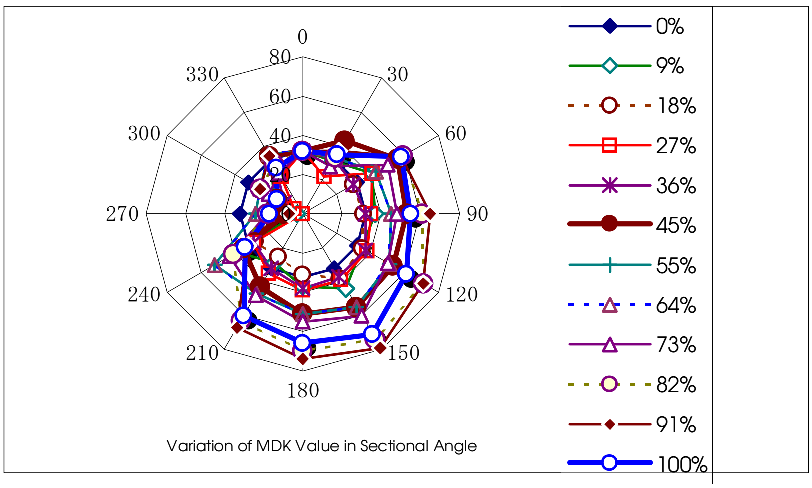


Fig.6 Variation of MDK Value in Sectional Area according to Fatigue Life

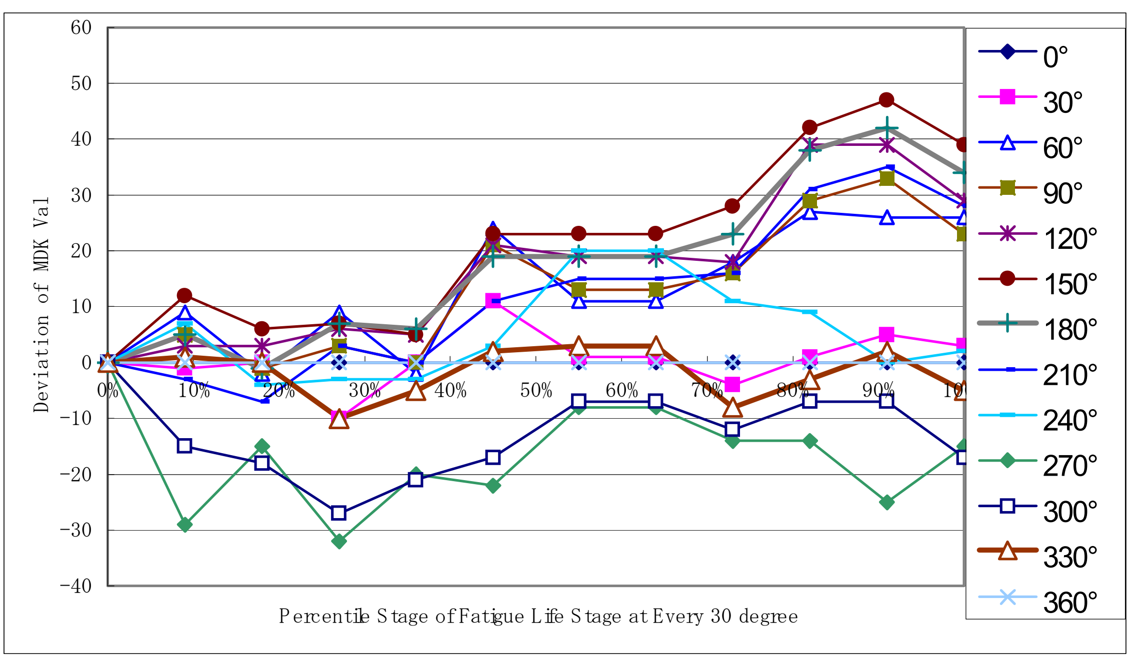


Figure 7 Deviation of MDK Value in Percentile of Life Stage at Every 30 Degree

It is revealed that a cyclic change of hardness by uneven nitriding can be clearly recognized and the MDK value changes according to the fatigue process. Also, the deviation of the MDK value was shown for the every angle of the specimen in Figure 7. To separate the change caused by the fatigue from by the nitriding unevenness, the deviation value is calculated on the base of that before tested condition in the EXCEL software.

From these results, it is supposed that the change of the MDK value of the nitrided material under the fatigue is smaller than that of the non-nitrided material. And it shows the change of the MDK value can indicate sensitively a change by the fatigue.

Under the high stress condition (loaded at 610 MPa), the fish-eye type flat mark (diameter is about 0.6 mm) of the fatigue crack has been recognized in the 6 mm diameter specimen.
The MDK sensor can detect the radial unevenness of the damage according to the fatigue process, and the tendency mentioned above is apparent after 50 % of the fatigue life. It is supposed the microscopic fatigue failure or the plastic deformation is inspected before the formation of the fish-eye crack.

## 6. Conclusions

There are a few methods to detect the inner imperfection, change of micro structure or crack initiation in the surface hardened steel, especially in the case of the materials having the complicated shape or the irregular thickness.

In this research, the magnetic change caused by the fatigue was detected as the MDK value, and determined. The process of the fatigue of the surface hardened steel was traced by the MDK magnetic sensor. And at the midst stage of fatigue life, the feature of the damage progress was detected. The possibility of the determination for the inner defects is shown, and the analyzing method is proposed to estimate the residual life stage of the fatigue.
The technique is mentioned as bellows;

From the fatigue test using the MDK sensor, the reference data of the material should be obtained according to the fatigue process. To estimate the residual life stage of the fatigue, the reference fatigue test should be obtained from MDK data fitting the life process.

## References


[1] US Patent 20040056654: "Magnetic field characterization of stresses and properties in materials", US Patent 20040056654, 2004.

[2] Onuki A, et al: "Fatigue Strength of An Ion-Nitrided Steel", Proceedings of 9$^{th}$ European Conference on Fracture (ECF9-Varna, Bulgaria), Sep. 1992, pp.381-386. Onuki A, and Numasaki Y:"Fatigue Strength of Ion-Nitrided Steel", Proceedings of 12$^{th}$ European Conference on Fracture (ECF12-Shefield, England), Sep. 1998.

[3] Makabe C, Makishi T. and Kaneshiro H: "Fatigue Mechanism of Ion-Nitrided Low Carbon Steel", Journal of Testing and Evaluation (ASTM), Volume 30, Issue 5, Sep. 2002.

**Supplements on MDK sensor**

**Principle and constitution of MDK sensor**

MDK (Magnetic Detector of Kaisei) sensor is a kind of electromagnetic induction sensor, which is developed and produced by Kaisei Engineer Co. Ltd. in Japan.

A sensor generates AC magnetic fields in the material, where lines of magnetic force can work not only on/in the surface layer but also into the material, and it is affected by the properties of the material. A schematic illustration is shown in Figure A.

Experimental results had shown this phenomenon is observed in the most metallic materials, including ferrous alloys, aluminum alloys and other nonferrous metals. The magnetic force, which is generated in the primary (sending reference signal) coil, penetrates a test piece and returns to the secondary (received detective signal) sensor coil again. But if in case there exists the uneven phase such as cracks, poor hardening, metal fatigue and plating detachment in the inside and outside of a test piece, lines of magnetic force change, while in penetrating, by means of these obstacles or disturbances, receive some influences and return to the sensor, as shown in Figure A.

The MDK sensor measures amplitudes and phases of voltage, which occurs on the sensor coil by received lines of magnetic force. Changes of amplitude show changes of conductivity of the material, and changes of phase indicate changes of magnetic permeability of the material. By measuring such changes, it is possible to decide whether it is passing or not.

**Examples of Application**

The MDK detector is used to inspect the detection of inner potential crack in weld line.

MDK sensor can detect the crack of T-type welded joint from the opposite side. Deference of wave amplitude is affected by the defects of material, especially crack-like imperfections; i.e. length, width and the shape of the flaw. Deviation of phase between the reference wave and detected wave is caused mainly by means of change of permeability of the material.

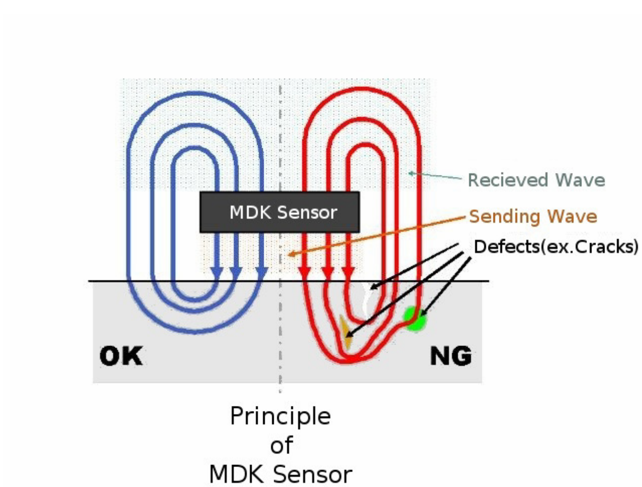


Figure A　Principle of MDK Sensor