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Technical Diagnostics of Equipment and Constructions with Residual Life Assessment Using the Method of Metal Magnetic Memory

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Abstract

The problems of metal components' residual life assessment and ways of their solution based on quick NDT methods are considered.

The article considers the abilities of the method of metal magnetic memory (MMM method) to detect crack initiation zones directly on equipment and to trace the development of metal fatigue failure process in these zones. Based on 100% power equipment inspection using the MMM method it is suggested to detect all potentially dangerous zones with developing defects and to timely remove them during the repairs. Thus, an opportunity is offered to assess the real equipment life.

According to ISO 24497-1:2007 (E) t**he method of metal magnetic memory** (MMM method) – is a non-destructive testing method based on the analysis of self-magnetic leakage field (SMLF) distribution on components' surfaces for determination of stress concentration zones (SCZs), imperfections and heterogeneity of metal structures and welded joints.

A specific feature, which distinguishing the MMM method from other NDT methods, is that it detects concentration of stresses on defects, i.e. evaluates the extent of their danger for damaging development and assesses the stress-strained state of metal and welded joints.
The MMM method and corresponding inspection instruments are used at more than 1000 Russian enterprises in various industries. Besides Russia, the method is introduces and tested at individual enterprises in 25 countries of the world.

Keywords: energy state, lifetime assessment, metal magnetic memory, non-destructive testing, residual life assessment, stress concentration zone, stress-strained state.

Introduction

The following problems of metal components' lifetime assessment should be pointed out among the principal scientific-technical problems:

- the lack of science-based concept of engineering diagnostics and lifetime determination;

- insufficient efficiency of conventional non-destructive testing (NDT) methods and devices at early diagnostics of fatigue damages and investigation of structural-mechanical properties of metal;

- low effectiveness of available techniques of reference strength calculation due to the lack of actual structural-mechanical properties of metal for all elements and units of metal components;

- absence in common practice of effective NDT devices and methods allowing to carry out 100% inspection of metal components in order to assess integrally the stress-strain state and the individual lifetime of each unit and aggregate.

Carrying out of 100% inspection of metal components using conventional NDT methods (UT, MT, etc.) is associated not only with the high level of costs, but it is ineffective because of their unsuitability for detection of fatigue damages at the early stage of their development.

As a rule, crack resistance is assumed to be a basic parameter, characterizing the metal's state of the equipment operating under the conditions of cyclic loading. It is necessary to keep in mind that this conditional characteristic of the material, which is determined by the ratio of the current (being actual at a specified time under specified conditions) rate of the crack growth to the critical rate for a material in question. However, this characteristic is determined on the specimens, and transfer of laboratory test results to real operating conditions does not provide the objective assessment of metal components' efficiency.

But is it possible to carry out assessment of the crack growth rate and to detect the zones of their development under real conditions directly on metal components?

1. A specific feature of the MMM method and its ability to assess of metal components' lifetime in SCZ.

It is known that the primary goal of the 100% inspection is to detect the potentially dangerous stress concentration zones (SCZs), in which the development of damages occurs due to corrosion, fatigue and creep. We suggest applying the Metal Magnetic Memory (MMM) method, which is primarily intended for detection of SCZs based on the quick inspection of the entire surface of metal components, exactly for solution of this problem. The method does not require carrying out of any preparatory works.

SCZs represent not only known beforehand areas, where specific features of the structure create various conditions for distribution of stresses induced by the external working load. But they also represent randomly located areas, where, due to the initial inhomogeneity of the metal combined with off-design additional working loads, large strains (as a rule, shear strains) occurred.

Paper [1] considers the physics of the metal's fatigue damaging and offers a pattern of this process development, which opens a possibility to quantitatively assess the material's state in case of the metal magnetic memory method application.

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Self-magnetic leakage field (SMLF) is a magnetic-leakage field occurring on the component's surface in the zones of stable slip bands of dislocations under operational or residual stresses or in the zones of strong material microstructure heterogeneity.

Reading of **SMLF** provides a unique possibility to integrally assess in the quick testing mode the actual equipments state taking into account structural inhomogeneity, distribution of residual stresses and macrodefects.

The basic diagnostic parameter according to the MMM method is the gradient of the magnetic leakage field H_p *(dH_p/dx)* or this field's variation intensity factor (K_{in}), which is recorded when scanning is carried out along the surface of metal components using the sensor of the specialized magnetometer. It was established that this very diagnostic parameter, due to the magnetomechanical effect, directly reflects the energy state of surface and depth layers of the metal in SCZs. At the same time the maximum value of the field gradient, determined on the surface of the metal with accuracy of up to 1 mm, corresponds to the source of crack initiation. The domain structure undergoes sufficient changes in the area of the most intensive process of strain and, finally, failure. The sizes of domains with directions, which coincide with the direction of glide, meet critical dimensions. As a result the domain with the maximum size "cracks" and a micro crack occurs. The method suggests considering exactly this state of the metal in a SCZ to be limiting when metal components are inspected using the MMM method.

The laboratory investigations on specimens under the conditions of static and cyclic loading resulted in obtaining of the energy ration between magnetic and mechanical parameters:

$$m = \frac{K_{in}^{lim}}{K_{in}^{ave}} = \left(\frac{\sigma_t}{\sigma_y}\right)^2, \qquad (1)$$

where K_{in}^{ave} and K_{in}^{lim} – are the magnetic field gradient values recorded in SCZs on the specimen or directly on metal components, respectively, when the conditional yield strength σ_y and conditional ultimate strength σ_t are met.

Fig.1 shows the graph of the field gradient K_{in} variation depending on the number of load cycles during the ∅108×4mm (steel 20) pipe specimen tensile testing at the maximum stress amplitude of 276MPa and frequency of 10Hz. The obtained graph characterizes the four stages of fatigue failure of the specimen's metal in a SCZ, which formed during the first 1000 cycles of the load application:

stage I – preparatory, consists in re-distribution of longitudinal non-uniformities of strain, which form under the created conditions a sequence being "convenient" for the metal. At this stage the process is characterized by a comparatively high velocity, and its duration is comparatively short – 1÷1,5% of the limiting number of cycles;

stage II – basic, accumulating, characterized by slow development of the process. Its duration is comparatively long;

stage III – intensive development of plastic stain, causing occurrence of micro cracks in SCZs, is observed (the stage of strengthening before failure);

stage IV – the period of a micro crack development into a macro crack right up to failure of the specimen.

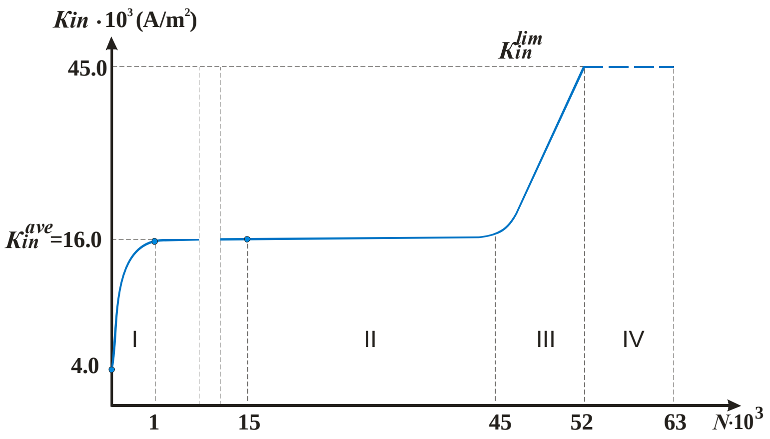

Fig.1. Variation of the field gradient in the SCZ of the specimen # 6 depending on the number of tensile load cycles.

The presented results of experimental investigations on a pipe specimen indicate the possibility to apply the metal magnetic memory method when the lifetime of real metal components is assessed.

The correctness of the ratio (1) was confirmed many times directly on metal components during inspection using the MMM method. According to the results of design calculations, presented in paper [1], the magnetic parameter K_{in} characterizes the density of the magnetic energy w_m, which is conditioned by the mechanical energy of strain due to the power exposure w_c:

$$K_{in} \sim \frac{w_m}{w_c} \sim \frac{2E}{\sigma^2}, \tag{2}$$

where E – is the elasticity modulus (or the plasticity modulus for plastic strain).

It follows from the ratio (2) that the more power energy w_c is spent on strain (while becoming lower!), the more magnetic energy w_m is generated. And it causes increasing of the measured magnetic parameter K_{in}.

While comparing the specimen's state during experimental investigations by the magnetic parameter K_{in} when it meets the yield strength σ_y relative to the state of the same specimen when it meets the ultimate strength σ_t, we obtain:

$$\frac{K_{in}^{t}}{K_{in}^{y}} \approx \frac{\sigma_t^{\,2} \cdot 2E}{2E \cdot \sigma_y^{\,2}} \approx \left(\frac{\sigma_t}{\sigma_y}\right)^2. \tag{3}$$

The energy ratio (3), obtained in the course of design investigations, confirms the correctness of the ratio (1), obtained as a result of experimental investigations. The more detailed consideration of the ratio (3) at the physical level is presented in paper [3].

Using the obtained ratios (1) and (3) between the magnetic and the mechanical factors of strain hardening, it is suggested to perform practical assessment of metal components' lifetime in SCZs based on the measured factors K_{in} and the actual non-failure operating time of a unit in question on the date of inspection T_{act}.

In case the average value K_{in}^{ave}, corresponding to the level of plastic strain in SCZs for the same-type units of equipment (determined by the results of practical measurements), the actual maximum value K_{in}^{act}, measured in the SCZ of the unit in question, and the actual non-failure operating time of a unit in question on the date of inspection T_{act} are known, then it is possible to calculate the limiting time of operation T_{lim} of this unit as follows:

$$T_{lim} = \frac{K_{in}^{lim}}{K_{in}^{act}} \cdot T_{act}, \tag{4}$$

where K_{in}^{lim} is known from laboratory or industrial investigations. And in case it is unknown, then K_{in}^{lim} is determined from the ratio (1) based on the measured value of K_{in}^{ave} and the known mechanical characteristics σ_y and σ_t.

Thus, the residual life of the inspected unit with SCZs will be:

$$T_{life}=T_{lim}-T_{act}. \quad (5)$$

The suggest method of determination of the metal's limiting state in SCZs and of metal components' lifetime assessment is based on the accepted assumption of linear time dependence of the process of plastic strain and metal fatigue accumulation. At the moment of inspection the magnetic parameter K_{in}^{act} characterizes the actual energy state of the metal in SCZs. At the same time it does not matter, how (according to what dependence on the load parameters) this energy state was achieved. In the course of time the metal in SCZs as if discretely transforms from one energy state to another. If we manage to record the values of K_{in}^{act} at different time periods (T), we shall obtain the linear dependence $K_{in}=f(T)$ by the fixed moments (points) of various energy state of the metal in SCZs. Taking into account that the magnetic parameter K_{in} reflects variation of the residual strain in SCZs, then, respectively, the linear law of plastic strain (strengthening) summation (accumulation) is true in this zone.

At present, based on the rich experience of pipelines and various metal components inspection, Energodiagnostika Co. Ltd. possesses quantitative values of K_{in}, characterizing the limiting state of the metal by strength conditions and the initial development of micro- and macro cracks. Methodical guidelines for lifetime assessment of metal components are developed based on the measured parameters of the magnetic memory of metal. Paper [4] considers the examples of the lifetime assessment. Processing of the results of metal components inspection by the MMM method is carried out using the program "MMM-System". The design calculation of the degree of the metal closeness in SCZs to the limiting state and calculation of the residual life are performed using the program "MMM-Lifetime".

2. Basic stages of metal components residual life determination using the MMM method and other quick NDT methods.

Fig.2 shows the block diagram of residual life determination of metal components using the MMM method. The principal distinctive feature of such approach towards the lifetime assessment is carrying out 100% examination of the test object (TO) with detection of all potentially dangerous SCZs, which represent the sources of damages occurrence in the course of further operation of metal components.

In 2005 the experts of Energodiagnostika Co. Ltd. developed the draft of the Russian National Standard "Methodical Guidelines for lifetime assessment of potentially dangerous objects based on the quick methods of engineering diagnostics".

Quick methods incorporate passive NDT methods, which use internal energy of the structures metal:

- the method of Acoustic Emission (AE);
- the Metal Magnetic Memory method (MMM);
- thermal (heat) control.

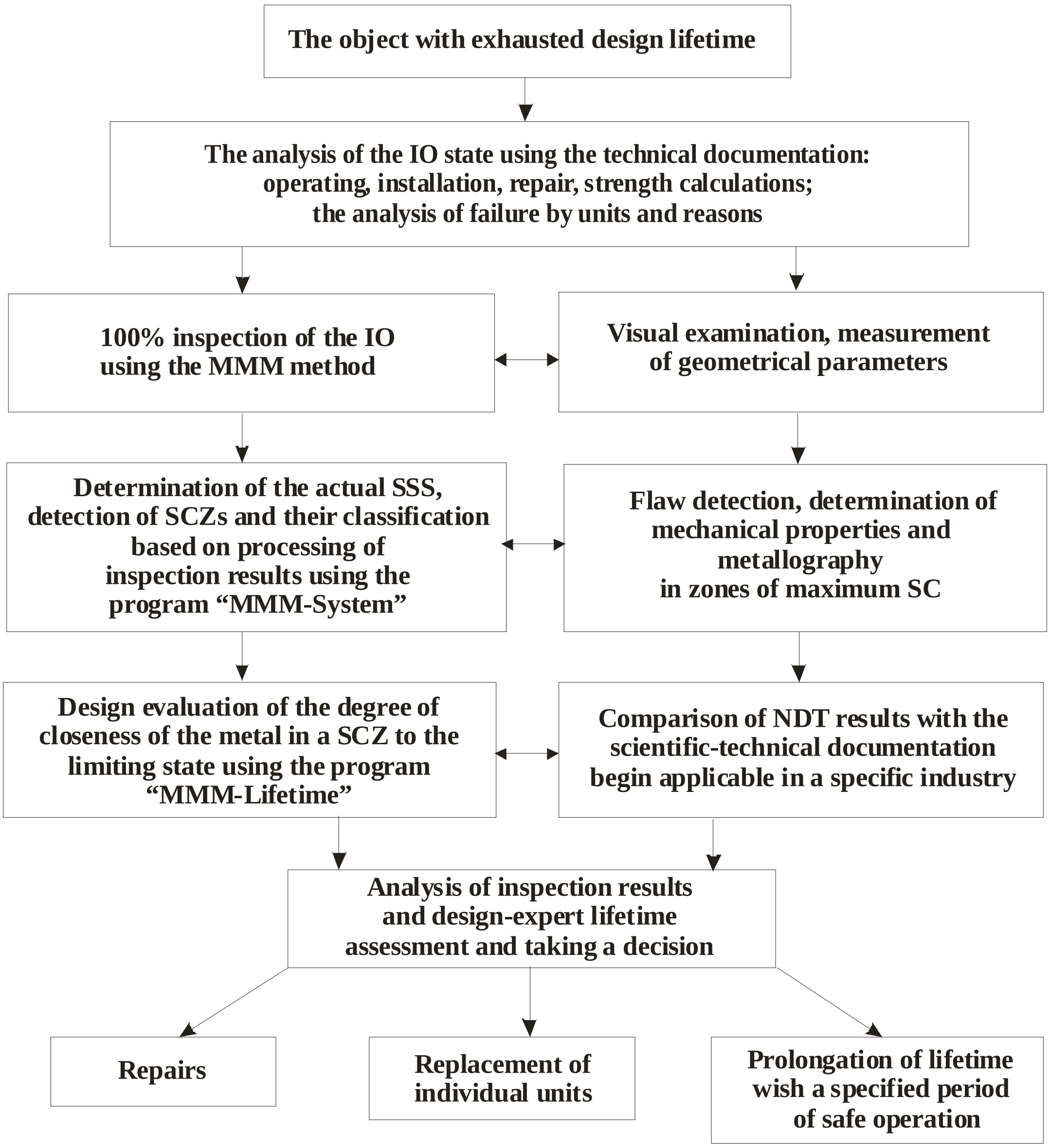

Fig.2. Block diagram of residual life determination of metal components using the MMM method.

These methods are nowadays most widespread in common practice for early diagnostics of damages on metal components and structures.

It should be noted that the development of the AE and the thermal methods ideology with the use of the similar energy ratio (3), obtained by the MMM method, will provide the opportunity to qualitatively change the status of these well-known methods by transferring them from the flaw-detection methods to the energy-diagnostic ones.

An important distinctive feature of the offered methodical guidelines (MG) as compared to the earlier developed guiding document GD 09-102-95 is the following:

- the more distinct determination of the role and tasks of modern methods of engineering diagnostics – 100% inspection and detection of stress concentration zones (SCZs), determining reliability and the residual life of metal components and structures. These tasks are set out in the new Russian National Standard GOST R 52330-2005. [5];

- it is suggested to use actual energy characteristics, which can be determined by the MMM, AE and thermal methods, as basic criteria of the limiting state of metal;

- the new requirements of Rostechnadzor of RF (the Russian Engineering Supervision) to the expert inspection of metal components and those of the Federal Law "About the Technical Regulation" are taken into account;

- the block diagram of the residual life determination is corrected with the stress on modern quick methods of engineering diagnostics;

- it is suggested to carry out reference strength calculations with residual life assessment for SCZs, remaining in operation, taking into account the revealed during inspection actual structural-mechanical properties of the metal.

When the offered MG are realized in practice, in most cases it is possible to provide expert assessment of the lifetime without performing complicated reference strength calculations based on complex inspection of metal components (see fig.2) and to specify the period of safe operation.

Based on the offered MG for specific metal components it is possible to develop the more precise technique for lifetime assessment, taking into account the specific features and requirements applicable in the industry in question.

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