PHYSICAL BASICS, PRACTICAL CAPABILITIES AND PURPOSES OF THE METAL MAGNETIC MEMORY METHOD APPLICATION FOR TECHNICAL DIAGNOSTICS OF CRITICAL INDUSTRIAL EQUIPMENT.

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Abstract:
At present, a fundamentally new NDT method based on the use of the magnetic memory of metal (MMM) is more commonly applied in practice. It uses the natural magnetization formed during the products fabrication and service life. The article considers the capabilities of the MMM method for assessment of the stress-strain state (SSS) and non-destructive testing (NDT) of various-purpose industrial equipments, in order to detect the segments where the development processes of fatigue damage are intensively propagate. Based on the 100% inspection of metal components using the MMM method, detection of all potential dangerously-affected zones – the stress concentration zones (SCZs), and the removal of these zones during repair, are carried out. Thus, there is a real opportunity to ensure the safe operation and lifetime extension of metal components based on their actual state.

Keywords: defect, diagnostics technique, magnetic memory of metal, non-destructive testing, stress concentration, stress-strain state.

1 Introduction
The concept of "Metal Magnetic Memory" was first introduced by the author in 1994. Before that time it was not used in the technical literature. The following terms and concepts were known: "Magnetic Memory of the Earth" - in archeological studies; "Magnetic Memory" - in sound recording; "Shape Memory Effect", due to structural and phase transformations oriented by internal stresses in metal products.
Fundamental differences of the metal magnetic memory (MMM) method from other magnetic non-destructive testing (NDT) methods were repeatedly reported in articles [1, 2], in the training handbook [3].
Theoretical studies were reported in researches [4, 5, 6]. Based on the established correlation of dislocation processes with the magnetic phenomena physics, the concept of "metal magnetic memory" was introduced in products’ metals and a new method of diagnostics was developed. The uniqueness of the metal magnetic memory method is that it is based on use of the self-magnetic leakage field (SMLF), occurring in zones of steady strips of dislocations sliding, stipulated by working loads action. SMLF occur because of domain boundaries formation at accumulations of high-density dislocations (dislocation walls). It is impossible to obtain an information source like a self-magnetic field at any conditions with artificial magnetization in working constructions.
Such information is formed and can be obtained only in a weak external field, as the Earth’s magnetic field is, in loaded constructions when deformation energy is a cut above the energy of the external magnetic field. It is shown in practical works that MMM can be used both at the equipment operation and after working loads relief during the repairs. Magnetic texture, formed under the action of working loads, becomes, so to say, "frozen" after unloading by virtue of the "magnetic dislocation hysteresis". Thus, there appears a unique possibility to evaluate the actual stress-strained state of the equipment and to reveal at an early stage maximal damage zones in metal by reading this information using special tools.

Physical fundamentals of SMLF occurrence are principally different compared to magnetic leakage fields (MLF) occurring on defects of products at their artificial magnetization used in well-known magnetic NDT methods. SMLF occurs in local zones (from 0.1 up to tens of microns) on the surface and in depth layers of products metal. Nobody has never performed investigation of SMLF and the physical fundamentals of its occurrence till "birth" of MMM (the 90-s of the last century). There was no such task at all! Researches reported in [2-6] gives more detailed description of the mechanism of SMLF formation in ferromagnetic products.

However, in connection with arising till date issues of metrological nature and those associated with the role of the MMM method with regard to its practical application [7], it became necessary to give answers to the most urgent of them.

Firstly, the main purpose of the MMM method is detection on equipment and structures of stress concentration zones (SCZs) - the main sources of damages development - in the express control mode using specialized instruments and scanning devices.

SCZs are not only pre-known areas where the design features create different conditions for distribution of stresses caused by an external load, but these are also randomly located areas, in which due to the initial metal heterogeneity combined with off-design additional workloads large strains (as a rule, shear strains) occur.

Geometric feature of magnetic anomalies that characterizes SCZs is the distance between self-magnetic field extreme values multiple of the standard size of a product (thickness, width, diameter). This distance corresponds to the minimum distance between the adjacent glide pads or the shell critical size occurring, for example, at the pipe stability loss.

Inspection by the MMM method is carried out without metal dressing and artificial magnetization. The method uses residual magnetization formed naturally during the products manufacture and in the course of their operation.

Of course, one can doubt the possibility of SCZs and various metal defects detection by magnetic anomalies on products with unknown prehistory [7]. However, it is known that the criterion of the truth is practice! Numerous studies carried out by the authors of the method at manufacturing plants showed that all products of the same type, made of the same steel grade and under the same technology, have almost the same distribution of the residual magnetization, and magnetic anomalies are only identified during the inspection in the areas of residual stress concentration and different structural irregularities on individual products. And this is not surprising, since during formation, for example, of thermoremanent magnetization of products in the course of their manufacture, internal stresses, and not the weak external geomagnetic field, play the decisive role.

In the course of products operation the initial residual magnetization (RM) is redistributed under the effect of workloads, and magnetic anomalies, caused by geometric displacements and product standard size, occur in SCZs.

If local SCZs do not occur in the same-type products under the effect of workloads, it the RM distribution pattern in them is practically the same. To make sure of this, it was necessary to inspect thousands of same-type units and products! Based on the established regularities and substantial
practical experience in inspecting various units of equipment and structures, the authors proposed a methodology of standardless calibration of inspection equipment and methods, as well as their respective metrology [3].

2 Diagnostics parameters in the MMM method.

1. In accordance with ISO 24497 [8-10] the MMM method is a non-destructive testing method based on recording and analysis of the distribution of the self-magnetic leakage fields (SMLF) that occur on products and equipment in stress concentration zones (SCZs). SMLF that reflects residual magnetization formed naturally during the product manufacture should be distinguished from magnetic leakage fields (MLF) occurring on metal defects and cracks at artificial magnetization of a product (for example, in the course of the magnetic particle inspection).

2. For quantitative assessment of the level of stress concentration (sources of damages), the gradient of the normal ($H^y$) and/or tangential ($H^x$) SMLF components is determined:

$$K_{in} = \frac{|\Delta H^y|}{\Delta x}, \quad \text{at } \Delta x \rightarrow 0 K_{in} = \frac{dH}{dx},$$

(1)

where $\Delta x$ - is the distance between the adjacent points of inspection.

In some cases during the inspection of equipment stress-strain state (SSS) the resulting SMLF gradient is used:

$$|H| = \sqrt{H^x^2 + H^y^2 + H^z^2}.$$

3. Among the basic calculation diagnostic parameters the MMM method uses the parameter $m$ that characterizes the ultimate strain capability of the material:

$$m = \frac{K_{in}^{max}}{K_{in}^{ave}},$$

(2)

where $K_{in}^{max}$ and $K_{in}^{ave}$ are the maximum and the average values of the field gradient, respectively, which are determined during the inspection by the MMM method of the same-type equipment units. Industrial and laboratory tests on the specimens established the relation between the limiting values of magnetic and mechanical parameters:

$$m_{lim} = \frac{K_{in}^{max}}{K_{in}^{ave}} \approx \frac{K_{in}^{lim}}{K_{in}^{int}} \approx \frac{\sigma_{lim}}{\sigma_t},$$

(3)

where the values of $K_{in}^{max}$ and $K_{in}^{ave}$, obtained as a result of the same-type equipment units inspection, correspond to the values of $K_{in}^{lim}$ and $K_{in}^{int}$, obtained as a result of tensile testing of specimens made of the same steel grade at achieving, respectively, the ultimate true strength at failure $\sigma_{lim}$ and nominal tensile strength $\sigma_t$.

Experimental studies also established that if the actual parameter $m_{act} \geq m_{lim}$, then in this case the limiting (critical) state occurs in the controlled equipment unit metal, at which a macrocrack forms. Physical substantiation of the parameter $m_{lim}$ can be found in papers [3, 4, 5]. Illustration of the relation (3) can be represented on the example of the results of a steel specimen tensile testing at a constant strain rate up to its rupture with simultaneous measuring of the specimen’s SMLF by the MMM method.

The relation (3) is used in the MMM method for assessment of the limiting state, at which a main macrocrack occurs and the damage development begins in the SCZ. According to evaluation in [5], the maximum detection accuracy of SCZs with the limiting state of the metal by the MMM method is not less than 90%.

Figure 1 shows the $\sigma$-$\varepsilon$ diagram combined with the graph of the resulting field $\Sigma|\Delta H|$ gradient modular values variation depending on strain $\varepsilon$, where the total value $\Sigma|\Delta H|$ was obtained by stage-by-stage summation of $|\Delta H|$ changes on individual sections from the beginning of tests in the point $A$ to the final point $K$ - the moment of the specimen rupture.

Let us use this example to calculate the value of the parameter $m$ by the relation (3) between the magnetic and mechanical characteristics.
σ-ε diagram section from point $G$, corresponding to the tensile strength $σ_t$, to point $K$ shows in a dotted line variation of the true stress in relation to the varying section in the specimen’s neck right up to the limiting (breaking) $σ_{lim}$ (Figure 1). For this specimen the value of $σ_t$, recorded on the tensile testing machine diagram, is equal to 458 MPa, and the design stress $σ_{lim}$ in relation to the final section area in the neck turned out to be equal to 990 MPa.

Then the value of parameter $m_{lim}$ for mechanical characteristics will be:

$$m_{lim} = σ_{lim} / σ_t = 990 \text{MPa} / 458 \text{MPa} = 2,16, \quad (4)$$

Then the value of parameter $m_{lim}$ for magnetic characteristics will be:

$$m_{lim} = \Sigma |ΔH_{lim}| / \Sigma |ΔH_t| = 214 / 106 = 2,02, \quad (5)$$

where $\Sigma |ΔH_t|$ and $\Sigma |ΔH_{lim}|$ - are total variations of SMLF modular gradients obtained when achieving of nominal tensile strength $σ_t$ and ultimate true strength $σ_{lim}$ respectively.

Thus, this experiment with steel specimen tension resulted in obtaining of a good confirmation of the relation (3) between the magnetic and mechanical characteristics.

Studies [5] demonstrate that the square root of the ratio $σ_{lim} / σ_t$ is equal to the average value of non-uniform strain $ε_{n-uni}$ in the neck area:

$$d = \sqrt{σ_{lim} / σ_t} ε_{n-uni}. \quad (6)$$

Relations (4) and (6) suggest the magnetomechanical relation, which characterizes the limiting strain capacity of the metal:

$$d_{lim} = \sqrt{m_{lim} \cdot ε_{n-uni}}. \quad (7)$$

where $d_{lim}$ - is a mechanical parameter characterizing the limiting strain capacity.

The MMM method uses the relations (6) and (7) for assessment of the metal’s limiting state, at which a main macrocrack occurs and the damage development begins in the SCZ.

According to evaluation in [5], the maximum detection accuracy of SCZs with the limiting state of the metal by the MMM method is not less than 90%.

It should be noted here that the opening of macrocracks at achieving the metal’s limiting state amounts to fractions of a millimeter, which is a dead zone for the majority of NDT methods.
Therefore it is incorrect to compare the results of inspection by the MMM method, for example, with the results of UT, X-ray or VT. And any comments about the MMM method on over reject or under reject are not acceptable. The methods used for confirmation of the results of inspection in SCZs with the limiting state of the metal are: metallography, hardness measurement or control performed, for example, by ultrasound at the search level.

If the values of the actual magnetic parameter $m_{act}$ are significantly higher than $m_{lim}$, i.e. $m_{act} > m_{lim}$, the size of cracks or various defects in SCZs become commensurable to the reject values in accordance with the existing norms for UT, X-ray, etc. And in this case, in the course of additional inspection by other NDT methods, such defects can be detected.

Combination of the results of inspection by the MMM method with other NDT methods dramatically increases the efficiency of inspection. At present the MMM method is widely used exactly in such complex inspection of the base metal and welded joints. SCZs are detected on the inspection object (IO) by the MMM method in the express-control mode without any surface preparation, then they are classified by the SMLF gradient and by the design parameter $m$, and after that the specified SCZs are additionally inspected by ultrasound or other NDT methods.

Classification of magnetic anomalies by sizes of defects located on the surface and inside the IO metal depth is possible, and the techniques of specific equipment units inspection using the MMM method are being developed in this area.

It should be noted that in various industries different standards for unacceptable defects in the non-destructive testing exist for identical inspection objects. Moreover, sizes of acceptable and unacceptable defects in the existing regulatory documents, as a rule, are insufficiently substantiated from the viewpoint of fracture mechanics. In this regard, it should be noted that an important feature of the MMM method is that it allows, using the parameters of magnetic anomalies in SCZs that already contain macrocracks of unacceptable sizes, to assess the extent of their danger, and to draw conclusions about the direction and intensity of their development. In conditions when the increasing number of metal damages on the long-term operated equipment has unexpected, fatigue nature, the MMM method, intended mainly for the early diagnostics of such damages, has obvious advantages over other NDT methods.

At present, more and more attention of experts is aimed at development of the technical diagnostics, lifetime and risk assessment, and monitoring the condition of the equipment. However, the "tragedy" of the situation is that, when assessing the limiting state of hazardous industrial facilities (HIF), experts working in this field face the fact that the existing regulations do not contain a clear definition of this concept from the viewpoint of fracture mechanics and materials science. Papers [5, 6] provide from the standpoint of modern knowledge of fracture mechanics a definition of such concepts as the "limiting state of metal" in a local SCZ of a structure and the "limiting state of the structural member itself". The MMM method allows to perform the equipment’s actual state assessment, adequate to the above concepts, in practical diagnostics based on (3, 6, 7).

From the standpoint of modern knowledge in the field of fracture mechanics and materials science about the metal’s and structural element’s limiting state, it is also necessary to develop new regulatory documents on technical diagnostics, monitoring and HIF lifetime and risk assessment. In conditions when it becomes possible, using the MMM method, to perform 100% equipment inspection and to identify all potentially hazardous zones, suspected to the damages development, lifetime and risk assessment becomes more specific and predictable [11].

In 2010 JSC STC "Industrial safety" supported by RSNTTD developed and put into effect a guidance document SDOS-05-2010 "Regulation on the certification of personnel in the field of stress-strain state non-destructive testing". Rosstandard TC-132 prepared and put into effect a number of national standards on "SSS Control". The demand for control of technical devices’
stress-strain state was featured in the "Rules for audit of industrial safety", approved by Rostekhnadzor Order No.538 of November 14, 2013. "Stress Control" as a new type of NDT was introduced in a series of guidance documents of PJSC "Gazprom" and other industries. However, in relation with the topic "Stress Control" there is still a lot of controversy when using in practice different methods and inspection devices for SSS control [12]. According to [13, 14], the main efforts of experts working in this field should be aimed at detecting SCZs - the main sources of damages development.

Currently the MMM method, to the author’s opinion, is the most suitable for the SCZs detection in practical diagnostics of equipment and structures. At the same time the MMM method allows to carry out assessment of the actual SSS of all structural elements in the express-control mode based on 100% examination.

Capabilities of non-contact magnetometric diagnostics (NCMD) of buried pipeline sections are of particular note. NCMD is also based on the regularities identified by the MMM method during the contact inspection. NCMD records magnetic anomalies in the geomagnetic field distribution caused by variation of the pipeline metal magnetization in stress concentration zones and in the areas of developing corrosion-fatigue damages.

Inspection of buried (or underwater) pipelines using NCMD must find an answer to the question: "When and where to expect damage or an accident?" Application of NCMD combined with the additional inspection of pipelines in the "prospect holes" (UT, eddy current, etc.) is aimed at solution of this problem. It is currently not possible to detect and classify developing defects in pipelines only based on the results of NCMD without any additional inspection in prospect holes. However, it should be noted that if, based on NCMD results, additional inspection detected unacceptable defects only in a few SCZs of a multitude of detected SCZs, such a result is sufficiently effective! Because it is known that even the one prevented accident, for example, on a gas or oil pipeline, covers all costs of NCMD performing.

3 Conclusions.

The main purpose of the MMM method and its application scope should be noted:
- Quick screening testing of mechanical engineering products’ quality for metal defects and local SCZs detection;
- early diagnostics of corrosion-fatigue damages and residual lifetime assessment of equipment and structures;
- defects detection (lamination, casting defects, etc.) in the deep layers of metal through the use of SMLF geometric parameters conditioned by dislocations glide pads in SCZs;
- 100% inspection of IO to detect local SCZs - sources of damages development;
- improving the efficiency of IO NDT due to application of the MMM method in combination with other NDT methods;
- reduction of material costs for performance of inspection due to refusing the use of artificial magnetization of IO and surface dressing (and in some cases - of insulation removal from IO).

The use of the MMM method provides the opportunity to study the metal’s structural and mechanical properties at the physical level during specimens laboratory testing.

The use of the MMM method applies to any products made of ferromagnetic and paramagnetic material. At present in power engineer, petrochemical, oil, gas and other branches of Russian industry the MMM method is included in a number of guidance documents and industry standards (more than 50 documents).
References


