Invited Lectures

AMAS Course on Nondestructive Testing of Materials
NTM'02 – (pp.9–20) – Warsaw, May 20-22, 2002.

Physical base of the method of metal magnetic memory

A. A. DOUBOV

Energodiagnostika Co. Ltd, Russia
mail@energodiagnostika.ru

On the basis of comparison of known thesis of dislocation processes in zones of a fatigue failure of metals and results of laboratory and industrial researches of magnetic parameters characterizing magnetization change in these zones, an attempt is made phenomenological to give interpretation of the physical foundation of the metal magnetic memory method – new magnetic method of a non-destructive inspection. The characteristic of qualitative and quantitative criteria used in the method of metal magnetic memory is shown.

1. Introduction

The method of magnetic memory of metal, in opinion of the author, represents an essentially new direction in engineering diagnostics. It is a second passive method after acoustic emission one (AE), which exploits the information of radiation of constructions. Thus MMM, except for early detection of a developing imperfection, in addition gives the information on an actual stressed-strained state of inspected object and detects the reason of formation of a zone of stress concentration – source of a damage development.

The peculiarity of the method of magnetic memory consists also in that it uses its own magnetic field of scattering (SMF) originating in zones of steady strips of dislocations sliding, stipulated by an action of working loads. In the presence of a weak magnetic field of the Earth in a zone of stress concentration on a surface of inspected object the gradient of a scattering magnetic field is generated and registered by specialised magnetometers. The mechanism of SMF influence on accumulations of dislocations is stipulated by fixing the domain boundaries, when these accumulations become commensurable with thickness of domain's walls.

For a quantitative estimation of a level of stress concentration the gradient (intensity of change) of the normal component of a magnetic field H_p is determined at the transition through a line of principal stresses (line $H_p = 0$):

$$K_{in} = \frac{|\Delta H_p|}{2l_k}, \tag{1.1}$$

where: K_{in} – the gradient of scattering magnetic field characterized by intensity of metal magnetization change in stress concentration zone (SCZ) and accordingly by the intensity of the change of H_p; ΔH_p – the module of the difference of H_p between two investigated points located on equal segments l_k on both sides from the line $H_p = 0$.

The new method of diagnostics, founded on the application of magnetic memory of metal allows to execute an integrated estimation of a node state in view of metal quality, actual service conditions and design features of the node.

2. What is essentially new in the offered inspection technique?

Known magnetic methods revealed the following obligatory conditions of their application. First, the magnetizing devices are necessarily used, and, secondly, known magnetic methods can be applied effectively only under the condition that locations of stress concentrations and imperfections in an object investigated are known in advance. Besides the known magnetic techniques of testing, as a rule, require cleaning of a metal and other preparatory operations. It is obvious that use of traditional magnetic techniques for testing of long structures and equipment is practically impossible under such circumstances. For example, the task to magnetize a specific pipe system, total length of which on the modern power boiler reaches 500 km, is unreal. To know beforehand locations of stress concentrations (basic sources of damages development) on each pipe of the boiler is obviously not possible because of influence on their formation of different technological, structural and service factors.

At the same time it is known that the majority of metallic structures and equipment made of ferromagnetic materials, under an action of working loads are subject to "self-magnetization" in the magnetic field of the Earth.

The scheme of displaying magneto-elastic effect causing growth of a residual induction is shown in Fig. 1. If cyclic load $\Delta\sigma$ acts in any location of a structure, and there is an external magnetic field (for example, the field of the Earth), in this place occurs a growth of residual induction and residual magnetization.

With the phenomenon of "self-magnetization" of equipment and structures they struggle everywhere (shipbuilding, power engineering, bearing and

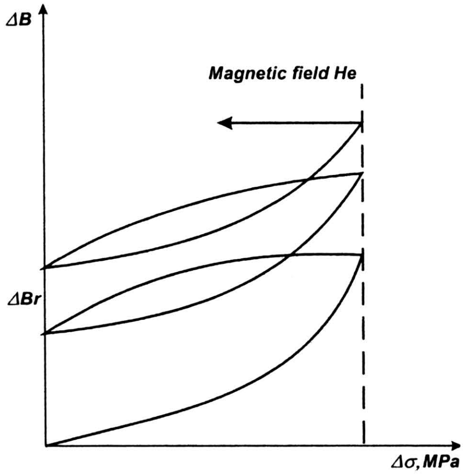

FIGURE 1. The scheme of magneto-elastic effect action: ΔB_r – the change of residual induction; σ – the change of cyclic loading; H_e – the external magnetic field.

other branches of industry). Having studied this phenomenon of magnetization on an example of operation of boiler tubes, it was offered for the first time to use it for the purposes of engineering diagnostics. At "self-magnetization" of the equipment and structures the different effects of magnetostriction are displayed. However, it is used at the new inspection technique an aftereffect (in all varieties of magnetostriction effects), which is shown as magnetic memory of metal to actual strains and structural changes in metal of the equipment.

The magnetic memory of metals or irreversible change of magnetization, stipulated by stresses exceeding an average level of internal stresses, originating on object of inspection under an action of working loads in a weak magnetic field of the Earth. For elements of machines and welded joints the magnetic memory of metal is shown as the residual magnetization, generated after their manufacture and cooling in the magnetic field of the Earth, and reflects their structural and technological heredity.

The method of magnetic memory of metals, being a method of nondestructive testing, based on the registration of own magnetic fields of scattering (SMF), arising on an equipment in zones of stress concentration under an action of working loads in the magnetic field of the Earth.

For separate details and workpieces, and also for welded joints MMM is based on the registration of SMF, arising in zones of residual stresses concentration after products manufacture and cooling in the magnetic field of the Earth. During the manufacture of any ferromagnetic materials (melting, forging, heat treatment), origin of a real magnetic texture occurs simultaneously with crystallization at cooling, as a rule, in the magnetic field of the Earth. The nodes of fixing of domain walls with an exit on a surface of workpiece as lines of the sign changeover of the scattering magnetic field H_p are formed in locations of the greatest concentration of imperfections of crystalline lattice (for example, congestions of dislocations) and heterogeneity of structure. Thus the line $H_p = 0$ will correspond to section with the maximal magnetic resistance and characterizes a zone of the maximal heterogeneity of metal structure and, accordingly, zone of the maximal concentration of internal stresses (ZSC).

3. Prospective model of magnetic dipoles forming in local zones of stress concentrations for ferromagnetic elements located in a structure

The processes of the change of the residual magnetization and the forming of magnetic dipoles in local zones of stress concentration (SC) from working loads occur under the following conditions:

- For example, the boiler tubes located in a closed magnetic circuit, have definite residual magnetization of the matrix and are in a constant magnetic field, as a minimum in the magnetic field of the Earth.
- Operating loads are action on tubes, and SC zones are formed under loading.

Notation used further in the text:

- M_t – the magnetization of tube metal (matrix),
- H_e – the magnetic field of the Earth,
- σ_{eq} – the equivalent stress in a tube from working load,
- σ_i – the internal stresses in the metal tube,
- $\Delta\sigma$ – not calculated additional stresses, for example, from a deficiency of self-compensation of the tube,
- τ – the tangential stresses,
- ΔM_σ – the increment (change) of the magnetization in a local the zone of stress concentration.

In real working conditions of the boiler tube on a segment exhibiting a lack of self-compensation (for example, at the presence of jamming in assemblies of the fixation) at the loss of stability, as a rule, bending with torsion arises. Under an action of external loads the appropriate field of stresses $(\sigma_{eq} + \Delta\sigma)$ with the maximal strain of metal is formed in the most weakened section of such a segment of the tube. Also, steady strips and platforms of dislocations arise. They slide in the same zone in a tube metal long before reaching a conventional yield stress of metal. It was established by special investigations on samples of tubes and plates [1, 2, 3] that the moment of initiation of steady sliding platforms is stipulated by a level and concentration of internal stresses σ_i (~70-80 MPa for steels 20 and 12Cr1MoV). At external loads reaching approximately 0.3 of the yield strength on a surface and in metal of a sample, in a zone of stress concentration there are generated bands of sliding dislocations are generated. They are described by a line of changeover of the sign of the normal component of the magnetic field H_p. At external tensile load reaching approximately 0.6 of the yield strength, in SC zones of the sample appears a share strain described by a development of the micro-plasticity on the whole section.

From the resistance of materials [4] it is known that the irreversible shears occur in the majority of crystals in their weakest planes, especially, if the last have a direction close to planes of the maximal tangential stresses τ. Thus the known contradiction between ideal and actual workpieces strength is explained by the fact that the displacement of atoms at shear occurs not on all plane simultaneously, but is due to distortions in a crystalline lattice, which are referred to as dislocations.

It expresses in forming of dislocations sliding bands. In conditions of repeating cyclic loads in the same location of the tube the sliding bands become steady and can expand with time deep into metal and in breadth of it.

The motion of dislocations on crystals is accompanied by the dynamic effects: mechanical, thermal, ultrasonic, magnetic, and electrical.

Under conditions when the strain energy required fot ordered motion of dislocations, by an order and more exceeds the energy of a small external field of the Earth H_e and internal field H_i due to the magnetization M_t, mechanical and magnetic moments of atoms of the crystalline lattice matrix, by virtue of magneto-mechanical effect, will orient not in a direction of the weak magnetic fields H_e and H_i, but in the direction of steady slide bands of dislocations. Thus the weak magnetic fields H_e and H_i take active part in forming of the total magnetic field resulting in ordered congestion of dislocations, both by a direction and magnitude.

Particularly, it is necessary to consider the mechanism of the origin of own magnetic fields and its influence on the congestions of dislocations and to answer a question whether in the absence of an external magnetic field of the Earth, only under stress concentration and deformations their existence is possible.

From physics of magnetic phenomena it is known that residual magnetization cannot arise in a ferromagnetic in the absence of an external magnetic field. Attempts to register origin of metal magnetization only by virtue of known magneto-mechanical effect under an action of mechanical stresses in the absence of an external magnetic field, as a rule, gave a negative answer [5]. Convincing evidence can be obtained with the help of the experimental set-up depicted in Fig. 2.

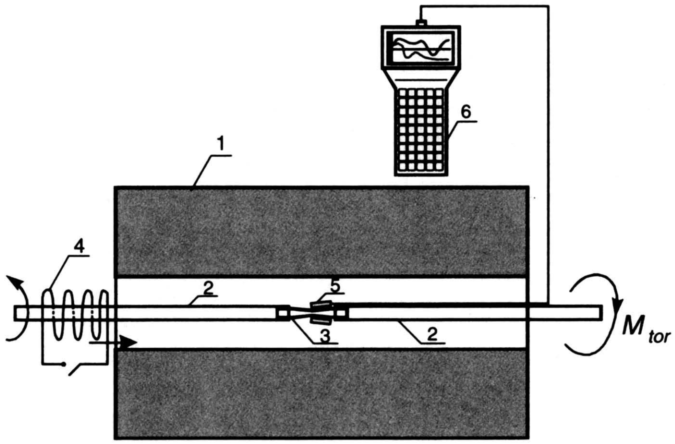

FIGURE 2. The scheme of the experimental set-up for gauging magnetic field on a surface of demagnetized ferromagnetic sample under condition of the absence of the internal field H_i and external field H_e: 1 – compensatory electromagnetic coil; 2 – circular rod of titanium (not magnetic) alloy; 3 – ferromagnetic rod of carbon steel (for example, steel 3); 4 – electromagnetic demagnetizing coil; 5 – ferro-sondes; 6 -magnetometer; M_{tor} – torque applied on the ends of a rod 2.

The experiment is performed as follows: at the beginning a circular rod 2 of the non-magnetic material (for example, made of titanium alloy) is manufactured and in the middle of it on a thread a ferromagnetic rod 3 of a carbon steel grade is mounted. Thus section of the rod 3 should be much less than section of the rod 2. A cone is grooved in the middle of the rod 3 in order to stipulate beforehand stress concentration in a zone of the magnetic field gauging. Also ferro-sonde transducers are fixed for gauging the tangential component (along an axis of the rod 3) of the magnetic field H_p^x in the conic part of the rod. It is known that the tangential component in the vicinity of the of ferro-sonde is equal approximately to the internal field H_i. Furthermore, with the help of the magnetometer gauging the field H_p^x on the rod 3 in the initial condition in the magnetic field of the Earth is performed.

Then the rods 2 and 3 are passed through a demagnetizing electromagnetic coil 4 and are interposed simultaneously into a compensatory coil 1, in which there is no external magnetic field (in Fig. 2 the direction of displacement of the rod 2 and 3 is indicated by the arrow). After demagnetizing of the rod 3 and location it at the center of the compensatory coil 4 gauging of the field H_p^x is done, and its zero value is registered.

Then the torque M_{tor} is applied to the opposite sides of the rod 2, and the magnetic field H_p^x is measured simultaneously on the rod 3 in a zone of stress concentration. With the help of M_{tor} the rod 3 is brought to fracture, and thus the magnetic field H_p^x is registered.

The experiments performed repeatedly in this way display the absence of the origin of the magnetic field H_p^x; accordingly, the field H_i and residual magnetization in the fracture zone of the ferromagnetic sample.

It is necessary to note that if similar experiment is performed with the previously demagnetizing rod 3 in the magnetic field of the Earth, the field H_p^x at the moment of the sample fracture increases from 5-10 A/m up to 100-150 A/m and more.

The results of the considered experiment convince one that the origin of own magnetic fields on accumulations of dislocations (and they necessarily should arise before sample destruction) is impossible in the absence of an external magnetic field.

The high values of scattering, observed in practice, of magnetic field in zones of steady sliding strips of dislocations (in zones of developing cracks) can not be explained by means of conventional concepts commonly used in the physics of magnetic phenomena. It is known that between magnetic moments of dislocations [6] there is no exchange of interactions, since the distances between them are significant. The accumulation of dislocations is considered as a paramagnetic gas and the very strong external field (about $10^6\epsilon$) is necessary for an appreciable magnetization of metal in this zone. Under considered conditions there is only the field of the Earth about 0.5ϵ (~ 40 A/m).

However, in real ferromagnetic products there is always a residual magnetization of the matrix M_t with appropriate DB position. Under the action of working loads (when the strain energy is higher than the energy of an external magnetic field) there is a displacement of the matrix DB in a zone of steady sliding strips of dislocations and their fixing in this zone, when the size of dislocations accumulations become commensurable with the thickness of wall domains.

It is evident that irreversible displacement and the fixing of the matrix DB in the zones of concentration of the working (and accordingly residual) stresses cause creation in these zones of their own scattering magnetic fields (OSMF) of considerable value.

From conventional concepts also follows [7] that direction and sign of the vector of residual magnetization inside a ferromagnetic determine only the external magnetic field. Such concepts follow from a great number of experimental works under conditions of simultaneous influence on ferromagnetics of loads of different sign and strong magnetic fields. The practical experience of testing of ferromagnetics by means of the metal magnetic memory method allows to assert that in zones of steady sliding strips of dislocations (the strain energy is on the order higher than the energy of the magnetic field of the Earth) the vector of the metal magnetization can change the sign and direction in accordance with the direction of sliding strips.

In the paper [1] it was observed that dislocation walls, as a rule, orientate themselves along the crystallographic direction (111) and trails of the plane (110). The dislocations lying in the plane of subboundary (110) form long-distance stresses fields just as stresses field from a flat accumulation of dislocations. The long-distance stresses fields form "long-distance" domain boundaries forming an own scattering magnetic field on the ferromagnetic surface along the stress concentration line ($H_p = 0$ line).

It is possible to presume that in SC zones the dislocation walls and matrix DB coincide (!). In this case it is possible to speak about magneto-mechanical effect appearing in considered conditions.

The magnetic field of the Earth in considered conditions plays a role of "inoculating" field without which the matrix DB could not exist.

The total magnetic moment from dislocation accumulations is negligibly small [6] and therefore could not be fixed in the absence of the magnetic field of the Earth.

We recall the fact known from the inspection of austenitic (paramagnetic) tubes: the value of proper scattering magnetic fields in SC zones (in zones of dislocations accumulation) does not exceed the value of the field of the Earth.

The inspection of boiler tubes after unloading showed that the SC zones (the centers of dipoles), correspond to the zero gradient of residual stresses. Moreover, on both sides from the centre of a dipole the zones of maximum values of H_p field correspond to zones of maximum residual stresses (tension or compression). This correspondence need to be proved by development of a special model. Such a model was developed in papers [8, 9]. Starting from introduced reasonings it is possible to make the following conclusions about conditions of origin of the proper own scattering magnetic field (OSMF) in SC zones in tubes and other equipment. OSMF are stipulated by three factors:

- by magnetic charges arising on dislocations accumulations and in zones of steady sliding strips of dislocations,
- by magneto-elastic and magneto-mechanical effects,
- by presence of a weak external magnetic field (as a minimum of the field of the Earth).

Due to the stable and directed dislocations sliding in SC zones on tubes surface magnetic dipoles are created which by virtue of magneto-mechanical and magneto-elastic effects reflect an intrusive link of stresses of kind I, II and III shown on micro- and macro-level simultaneously.

4. Prospective model of magnetic dipoles forming in local zones of stress concentration for ferromagnetic products (new and used) located outside of a construction

It is well known [7, 10] that if a ferromagnetic specimen is placed in an external magnetic field H_e, the distribution of residual magnetization M in it (after switching of the field off) and total magnetic moment are determined by the direction of the field H_e, shape of this sample and by the demagnetizing factor N (see Fig. 3). At gauging of the normal component of the field intensity H_p its approximate distribution is introduced in Fig. 3a with a zero value of this field in the middle of the sample. Thus the distribution of the residual magnetization M is found according to the scheme, introduced in Fig. 3b.

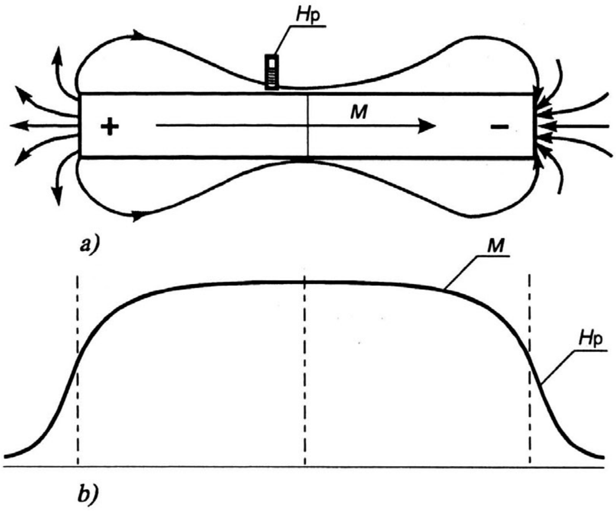

FIGURE 3. Prospective model of magnetic dipoles.

As we already know, basic technological procedures (fusion, forging, heat treatment) during manufacture of metal products occur at presence, as a minimum, of the external field of the Earth, and all products, as a rule, have a structural inhomogeneity. Therefore at cooling of metal products below the Curie point a magnetic texture is formed simultaneously with the crystallization in the magnetic field of the Earth according to the heterogeneity of the structure. Thus on the large accumulations of dislocations and other heterogeneities of the structure DB are formed, and after cooling of the product the distribution in it of residual magnetization, as a rule, will not match to its ideal distribution, introduced in Fig. 3b. The internal stresses (σ_i) of kind III and II (accordingly at the level of the crystalline lattice and the level of a grain) participate in forming of a real structure of metal products.

As a result of laboratory and industrial investigations it has been established that in real products the line $H_p = 0$ can be situated in different zones and it corresponds to the place of flaws concentration and the line of internal stresses concentration (SC line). The SC lines, depending on their disposition in concrete products in relation to the direction of external load action, can provoke their strengthening or, on the contrary, loss of the strength.

To corroborate this conjecture special tests on samples of ferromagnetic steel were carried out by a machine for tensile fracture [3]. It was shown that the sample with perpendicular disposition of the SC line to the direction of the external load has the reduced strength as compared to samples on which the SC line was located under a corner or coaxial with the external load.

Figure 4a provides an illustrative example of the distribution of the normal component of the field H_p, registered along the generatrix of the electric motor shaft, and the location of the SC line, being described by the line with the zero value of the field H_p.

Figure 4b illustrates the brittle fatigue fracture of the similar shaft on the line $H_p = 0$. Performing the measurements of the field H_p on the boundary

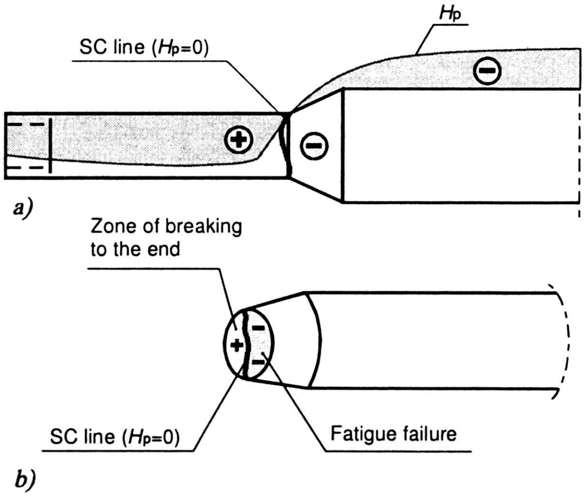

FIGURE 4. Brittle fatigue fracture of shaft.

of a fatigue fracture line the change of the sign of this field (line $H_p = 0$) is registered. This example obviously demonstrates the validity of established regularity for products being exploiting. The line of the sign change of the normal component of the field H_p on a surface of a product (or platform, on section) corresponds to lines of changeover of the sign of the strain.

In the proposed method of testing [11] the basic quantitative criterion is the gradient of the field H_p, registered at perpendicular intersection of the SC line ($H_p = 0$ line, see formula (1.1)).

Thus the gradient of the field K_{in} characterizes the density of accumulations of dislocations ρ in the volume of the specimen (on width and depth) in a zone of stress concentration (in the zone of the location of the sliding platform). The zone of the fatigue fracture introduced in Fig. 4b is, obviously, the platform of sliding of dislocations, which took place before the fracture of the shaft.

It is necessary to note that in the paper [12] the sizes (depth and width) of steady sliding strips of dislocations from one micron (at the stage of their sure fixing) up to tens and hundred microns (at a stage of their transformation in a crack) are indicated.

There are many practical examples where the grinding of a metal along the line $H_p = 0$ the depth $\sim 0.5 \div 0.6\,\mathrm{mm}$ completely eliminated the line $H_p = 0$ appropriate to steady sliding strip of dislocations. The maximum depth of sampling of metal before complete deleting of steady sliding strips of dislocations (before disappearance of $H_p = 0$ lines) is fixed while in practice it amounts to $3 \div 4\,\mathrm{mm}$. At metallographic analysis of metal along $H_p = 0$ line the micro-cracks of size from units up to several tens of microns were repeatedly arrested. Such cracks are located outside sensitivity region of conventional inspection methods. Obviously, the "critical" size of steady sliding strips, preceding the formation of macro-cracks, depends on mechanical properties of metal of the tested object.

According to [13], the internal stresses σ_i, originating in accumulations of dislocations, are proportional to $\sqrt{\rho}$. It is known that the steady sliding strips of dislocations and, accordingly, their maximum accumulations occur in the case of shear strain under the action of the tangential stress τ. According to [14], the tangential stress is proportional to $\sqrt{\rho}$:

$$\tau = A\,G\,b\sqrt{\rho}, \tag{4.1}$$

where: A – the constant, equal to $0.3 \div 0.6$; G – the shear modulus; b – the Burgers' vector.

Hence we conclude that the gradient of the field K_{in} in the proposed method is proportional to the density of dislocations and, accordingly, to σ_i.

The method of definition of the limiting metal state in SC zones according to magnetic field gradient K_{in} is patented in Russia, Poland and China [15].

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