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The metal magnetic memory method in the diagnostics of power machinery componen

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Analysis and modelling

ABSTRACT

Purpose: The paper presents the metal magnetic memory method and its application for industrial non-destructive testing. Special emphasis was put on the use of the method for the testing of power equipment and machinery components.
Design/methodology/approach: The use of the strength of the residual magnetic field in diagnostics provides macro-scale information on: material discontinuities, defects of the material structure, load history of the component, and the distribution of stresses.
Findings: A wide range of applications of the metal magnetic memory method was presented. In many applications, the use of the method provides information which cannot be obtained by means of traditional, standard methods of non-destructive testing (NDT).
Research limitations/implications: The metal magnetic memory method can be used for the testing of all ferromagnetic materials and those austenitic steels in which, due to mechanical or thermal load, delta- or sigma ferrite appears.
Practical implications: The metal magnetic memory method, as any NDT method, has some usage limitations which result mainly from the structural features of the components under examination and external conditions. Any application of the method for a specific component calls for the development of a research methodology which takes into consideration the load state of the component during examination and the values of the external magnetic field at the place where the examination is being carried out.
Originality/value: Possibilities to use the metal magnetic memory method as a defect detection method were presented. Test results were shown which point to significant capacity of the method for detecting areas prone to initiate cracks and cracks in the early stage of their development.
Keywords: Residual magnetic field; Metal magnetic memory method; Non-destructive testing

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1. Introduction

The residual magnetic field (RMF) of a ferromagnetic material is a value affected by several physical effects. These are: the magnetomechanical effect, the effect of magnetic field leakage caused by macroscopic discontinuity or structural inhomogeneity of the material, and the processes of mutual interacting of magnetic fields with dislocations and their accumulation [1-7].

The influence of stresses on magnetic properties is described by the magnetomechanical effect. In a ferromagnetic material placed in a magnetic field the strength of magnetization varies according to stress. The change in magnetization has a reversible component that fades after unloading, and a constant component. The relation between the stress and strength of magnetization is a complex one. The strength of magnetization depends on the type of material, the strength of the magnetic field, the magnetic history, strain and temperature. Local load changes in the ferromagnetic material will involve local changes in the strength of magnetization. This is the reason why the distribution of the RMF reflects in a way the distribution of strain (stress) of the component in question [1-6].

In the manufacturing process, the magnetic texture of the metal is formed as the metal cools down below Curie point, together with crystallization in the magnetic field of the Earth. Inhomogeneity of the crystal microstructure of materials results in a creation of obstacles, to locally and temporarily pin the domain walls when they move under a magnetic load [2-4]. These obstacles arise where there is a high concentration of microstructural inhomogeneity and defects in the crystal lattice (e.g. dislocation clusters). According to the theory of fracture mechanics, the initiation of fatigue cracks is expected in the areas of concentration of dislocations (at inclusions or grain boundaries) which trigger the local plasticization of the material. The zones of plasticization produce local magnetic anomalies whose size depends on the level of stress and the constitution of the material. [9]

The non-destructive testing method which makes use of the strength of the RMF is the method of metal magnetic memory (MMM) testing [1-6]. It has been widely used both as a strictly defect detection method focused on finding the already existing material discontinuities, and as a method which makes it possible to define the areas in the component which are most prone to the potential development of discontinuities. Additionally, research is are now in progress to work out diagnostic algorithms which allow the assessment of the level of stress and wear on the grounds of the strength of the RMF [9-15].

The paper offers basic information on the method of the metal magnetic memory testing and presents the method application in the power sector and other industries.

2. The method of the metal magnetic memory testing

The method of metal magnetic memory testing is a passive method of non-destructive testing based on the recording of the residual magnetic field of a component that results in the areas of the slip bands of dislocations dependent on the effect of working loads [16-17]. In the MMM testing the distributions of components H of the magnetic field are recorded at the surface of the inspected components. One of the diagnostic parameters of the metal magnetic memory method is the line of the polarity change of normal component H_n of the magnetic field - line H_n=0. The mechanism of the formation of the line during the operation of machinery components has not been fully explained yet. In this case there are just hypotheses. The load affecting a component during operation produces in it a specific distribution of stresses. According to [16], micro-plasticity and a permanent shift of dislocations will occur if the stresses resulting from external loads exceed the level of internal stresses (for carbon steels the level of internal stresses is not higher than ~0.3R_e). According to [18], the shift of dislocations will occur if shear stresses in the slip planes of dislocations are higher than the value of the critical stress of the slip of dislocations (from ~0.3R_e to ~0.5R_e). In the areas of permanent bands and planes of slip, due to the overlapping of magnetic planes and slip planes of dislocations, domain boundaries and own magnetic field are formed naturally. So oriented location of the domains on the slip planes of dislocation formed in dynamic conditions under load is maintained also after unloading [16,19,20]. Exceeding the level of internal stresses results in a dramatic change in the magnetic field of the component. In the area of the formation of slip bands, the vector of magnetization inside the metal is formed not in the direction of the external magnetic field but in the direction of the slip planes [17]. The areas of shear deformation on the surface of the components are characterized by the lines of the polarity change of normal component H_n (lines H_n=0), or by an abrupt change in the magnetic field of one sign, directed along the slip planes [16]. Additionally, more information can be found in literature [21] that the change of the sign of the normal component of the residual magnetic field occurs with the change of the sign of stresses and the transition from elastic to plastic strain. The course of the line is consistent with the direction of the smallest principal stresses occurring in the tested component, and shows the direction of the development of potential cracks which can appear in it [22]. According to [23], the location of the lines of the concentration of stresses in the area of the quasi-elastic load (σ=0.9R_e) corresponds to the sections of the sample which have the greatest number of local sections of plastic deformation. The location of the lines of concentration of stresses within the areas of plastic deformation (Chernov-Lüders front) corresponds to the sections of the sample with the highest number of areas of local plastic deformation with an increased density of dislocations. In [24] it was found that the position of the line of the polarity change on the surface of the component varied if load was applied.

If this line also coincides with the area of a large value of the gradient of the changes in the magnetic field, we talk about the place of stress concentration where defects and the processes of durability loss develop the fastest [22].

In order to quantify the level of stress concentration, the gradient (the intensity of the change) of normal component H_n and tangential component H_t of the magnetic field at transition across the line of the polarity change (line H_n=0) - the line of stress concentration - is determined.

$$K_{in} = \frac{|\Delta H_i|}{2\lambda_k} \tag{1}$$

where:

K_{in} - the gradient of the residual magnetic field or the magnetic coefficient of the intensity of stresses describing the intensity of the changes in the state of magnetization of the metal in the areas of stress concentration and, accordingly, the intensity of the change of field H_p;

$|\Delta H_i|$ - the modulus of difference of the value of normal component H_n or tangential component H_t between two inspection points located at equal distance λ_k on both sides of line $H_n=0$.

Segments λ_k must be perpendicular to line $H_n=0$. The perpendicular location of segments λ_k to line $H_n=0$ depends on their concurrence with the direction of the maximum principal stresses [1,2,25]. When the sensor of the scanning instrument perpendicularly cuts across the line of the polarity change, the value of the gradient of normal component H_n, as a rule, exceeds twice or more times value K_{in} obtained in the scanning along line $H_n=0$. An interpretation of line $H_p=0$ as the line of principal stresses was presented in [1]. The line shows the location of the slip plane, perpendicular to which the maximum tensile stresses - and along which the maximum compressive stresses - act. The ratio of the gradients of normal component H_n on the lines of the polarity change during perpendicular and longitudinal scanning is conditioned by the known dependence of normal and shear stresses in the shear plane [26].

Absolute values $K_{in,max}$ corresponding to the state of metal just before the active development of a defect in industrial conditions are affected by the following: the size and the form of the object of inspection, corrosion, creep, residual welding stresses, the depth at which the damage occurs, and other causes. That means that, while working out the test results with the use of boundary value $K_{in,max}$, the possible causes of damage should be taken into consideration. In order to give more exact boundary gradients of the field ($K_{in,max}$) corresponding to the boundary states of the metal of the component before damage, statistical data of the results of the method of metal magnetic memory testing together with the results of other NDT methods should be collected [12,26].

3. Predicting the exhaust of the durability of teeth in toothed wheels on the grounds of the RMF analysis [13,27,28]

Defect detection tests of toothed gears are focused on finding damage that has already developed. This, however, is not enough to ensure reliability and to exclude the possibility of failure in the course of further operation. The times between overhauls of toothed gears are so long that defects of sizes below the threshold of sensitivity of traditional defect detection methods can develop and ultimately lead to the gear being damaged. It is necessary to complement the scope of diagnostic testing with a method that allows the finding of defects of the teeth in the early stages of their development.

Each entry of the tooth into the tooth contact produces in it a cyclic change in stresses. Each cycle of the change in stresses in a ferromagnetic component results in an increase in residual magnetism, i.e. a change in the residual magnetic field of the component due the magnetomechanical effect. Additionally, the tooth surfaces which transmit load during operation are subject to strain, i.e. local zones of plastic deformations occur on them. The RMF of the tooth is the resultant of the effect of the above-mentioned interrelated factors. Studies have shown that there is a connection between the number of the cycles of changes in load, the value of the load and the distribution on the width of the tooth, and the values of the magnetic field components. It has also been found that some symptoms which anticipate the fatigue damage to the tooth can be observed in the distributions of the RMF. If the distribution of the residual magnetic field in the teeth is characterized by a local sudden change in the value of the tangential component (most often related to the change in the sign of the component, i.e. the occurrence of value $H_s = 0$) and an occurrence at that point of the local extremum of the normal component, the probability of failure of the teeth is considerable.

Sample results of the examination of the RMF of the teeth of a pinion are given in Table 1, where the black line denotes tangential component of magnetic field H_t and its gradient dH_t/dx, the red line - normal component of magnetic field H_n and its gradient dH_n/dx. Analyzing the distributions of the magnetic field in this pinion, it was found that approx. 30% of its teeth showed symptoms of a highly probable fatigue damage. The conducted liquid-penetrant and ultrasonic examinations did not give indications of potential cracks. The pinion was put to further operation. After a few months several teeth got broken - Fig. 1.

A large number of toothed wheels in operation were examined and no such symptoms were found in them. They continue to operate failure-free.

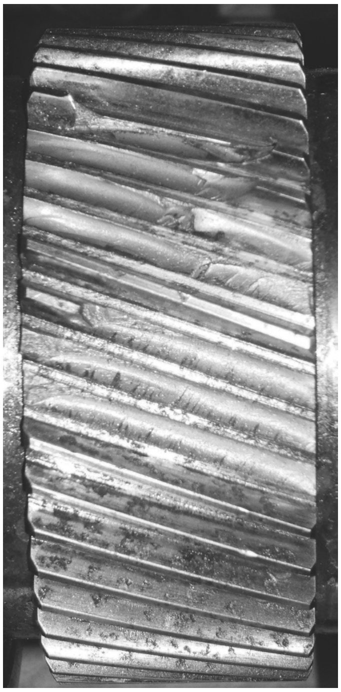
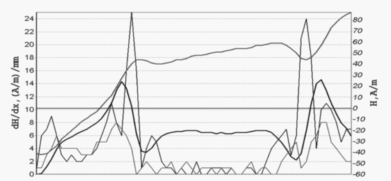
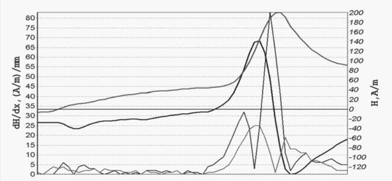
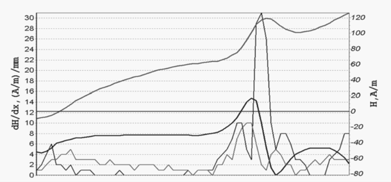
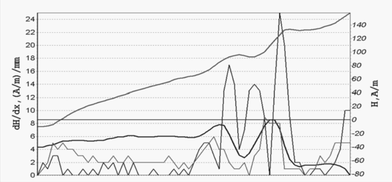
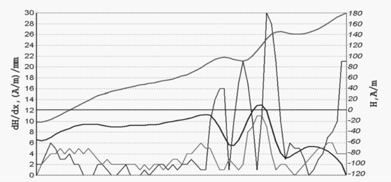
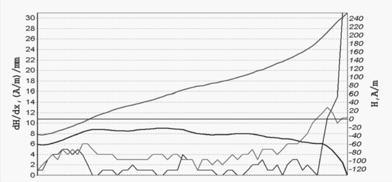


Fig. 1. Teeth after failure [29]

Table 1.
Sample distributions of the tangential component (black line), the normal component (red line) and their gradients [27]

Tooth number	Chart	Tooth number	Chart
3		6	
13		15	
16		35	

4. Determining cracks and the direction of their course and points threatened with cracks in the rotors [29] and blades [30] of power machinery

The presented object is a compressor rotor in which cracks of two of its blades were found during repair. The cracks were located in the inlet area.

The cracked fragments of the blades were cut out and the rotor was put to further operation. When the machine was re-opened cracks, were found on the shortened blades. The measurements of the RMF were carried out on the surface of the blades. Fig. 2 is an example of the test results for the cracked blades, and Fig. 3 is representative of the results obtained for the remaining long blades. The horizontal graphs refer to the inlet edge, the vertical ones - to the side edge. The thick lines in the graphs are the values of the components of the magnetic field: normal component H_n (blue), tangential component H_t (red). The thin lines are the values of the derivatives [28].

In the blades where cracks were found on the inlet edge, a polarity change of the normal component and areas of significant concentration of stress occur. In the other blades there are areas whose magnetization level exceeds the measuring range of the instrument. These areas are located close to the rotor inlet. Such a high level of magnetization testifies to the heavy strain that these blade areas were subject to during operation. The strain probably results from the vibrations of the blades caused by the rotation of the rotor and/or the pulsations of the agent flow. The lines of the polarity change of the normal component determined on the blades are oriented in the direction of the crack in neighbouring blades and show the most probable direction of the cracks in the so far undamaged blades. Fig. 4 and Fig. 5 show that in the vicinity of shortened blade D14, in which a crack was found, the lines of the polarity change of the normal component of the magnetic field which were determined on blades D1 and D2 are oriented in accordance with the course of the crack in blade D14, i.e. from the inlet edge towards the rotor hub.

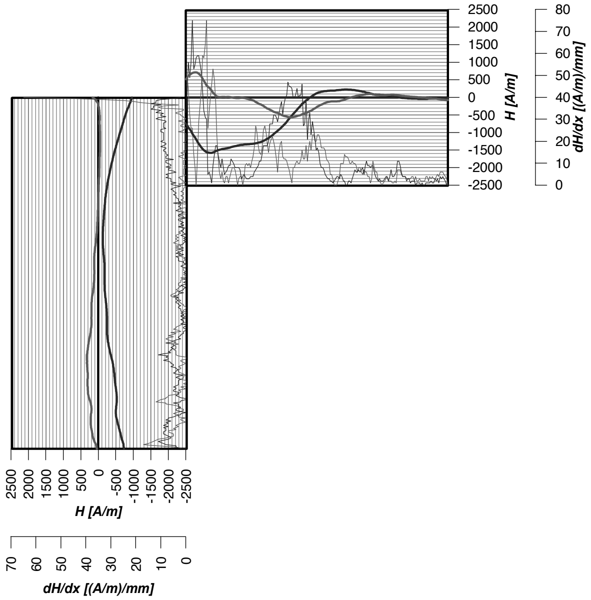


Fig. 2. Blade D14 – shortened [29]

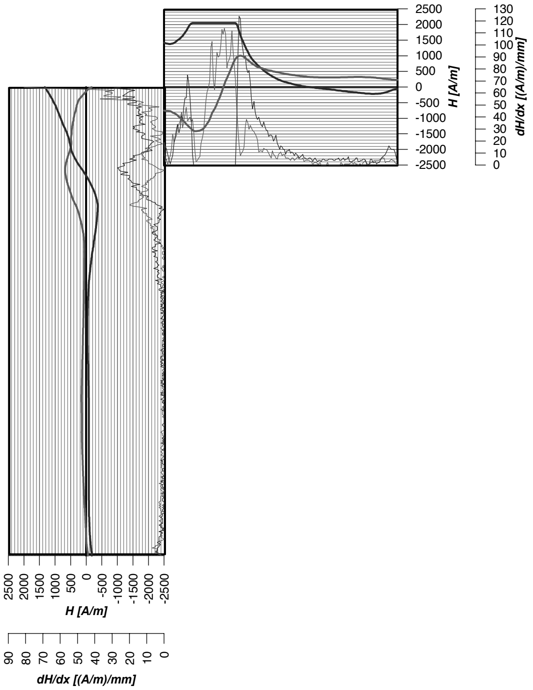


Fig. 3. Blade D1 [29]

On the other hand, in Fig. 6 the lines of the polarity change of the normal component of the magnetic field which were determined on blades D6 and D8 are oriented in accordance with the course of the crack in blade D7, i.e. from the inlet edge towards the side edge [29].

Damage to turbine blades is typically caused by their fatigue cracks (fractures). To initiate and develop such fractures, in most cases, blade vibrations are needed (as they produce extra strain caused by the bending and/or torsion of the blades), and the fracture usually originates at the point of additional concentration (accumulation) of stress caused by the geometrical, constructional or structural notch effect.

Fig. 4. Courses of the line of polarity change in blades D1, D2 and D13 [29]

Fig. 5. Damaged blade D14 with visible crack in the internal direction [29]

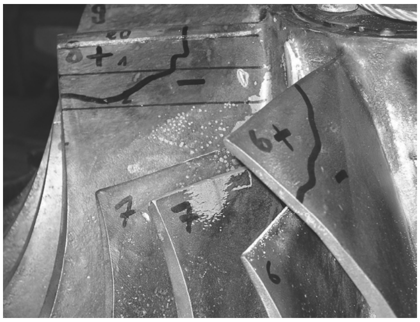


Fig. 6. Courses of the line of polarity change in blades D6, D8 and visible crack in blade D7 in the direction of the side edge [29]

The initiation and propagation of cracks is always accompanied by a stress field. The MMM method, by means of the measurement of the size and nature of the distribution of residual magnetism (related to the stress field), makes it possible to find the point at which such a concentration of stresses occurs. Even if no discontinuity was found at the place where the stress concentration zone (SCZ) occurs, this is where there is a higher risk of the initiation and development of a fracture during further operation. A significant advantage of the method is the fact that the testing can be conducted with no special surface preparation which is required for other testing methods - prior cleaning will suffice. Testing with the MMM method should be carried out first, even before the blades are disassembled, so as not to disturb the magnetic state of the material [30].

5. Testing of welded joints [31-33]

The defects in welded joints are potential stress concentrators. But stress concentration in a welded joint does not have to be the result of only the occurrence of defects. Looking more broadly at the problem of stress concentration, the welded joint, due to the notch effect and thermal deformations after welding, is a stress concentrator itself. Therefore, not all indications obtained in the MMM testing are defects in the common, standard meaning. Some of the indications of the method of the MMM testing of welded joints can result from the occurrence of a non-uniform distribution of stress after welding [34]. On the other hand, a question arises whether all defects of welded joints which can be detected by means of standard methods of non-destructive testing yield indications in the MMM testing. The results obtained in the MMM testing were compared to the results of the radiographic testing (RT). Welded joints in austenitic and ferritic steels were examined. The obtained results show that at the present stage of development the method of the MMM testing does not guarantee the same effectiveness of defect detection as the RT method used as the reference method. This applies particularly to the testing of weld seams at the production stage. The imperfections of the weld seams visible in the radiograms did not always give unequivocal and clear indications in the method of the MMM testing. It was not established which of the RMF components was best suited as a diagnostic signal. For the welded joints under examination, a clear indication of a defect, if there was any, usually occurred in the image of only one component; for other components the indications were none or barely visible. Sample test results are shown in Figs. 7-9. In the detection of defects of weld seams already in service the method of the MMM testing works much better. The imperfections which occur in weld seams, by concentrating stresses from working loads, create favourable conditions for the development of cracks. At the same time, due to the magnetomechanical effect [2,4,5] they result in indications of the method of the MMM testing.

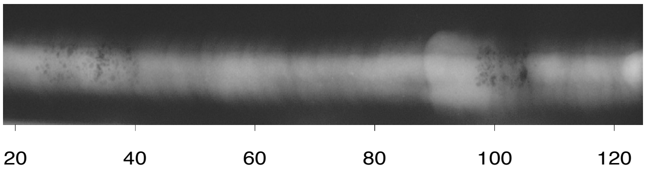


Fig. 7. Radiogram of joint A, welding incompatibility 30 ~ 60 mm - bubble cluster (2013); 140~ 160 mm - bubble cluster (2013) [32]

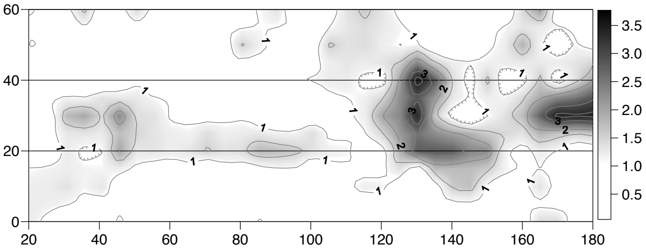


Fig. 8. Magnetogram m - $H_{t,y}$ of joint A, indications: 30 ~ 50 mm - SCZ coincides with the location of the occurrence of the defects of the weld seam; 120 ~ 150 mm - SCZ partly coincides with the location of the occurrence of the defects of the weld seam; the area of the largest values of m are probably the place of arc reignition, which may also suggest the occurrence of imperfections 517 or 601 according to standard EN ISO 5817; 160 ~ 180 mm - SCZ [32]

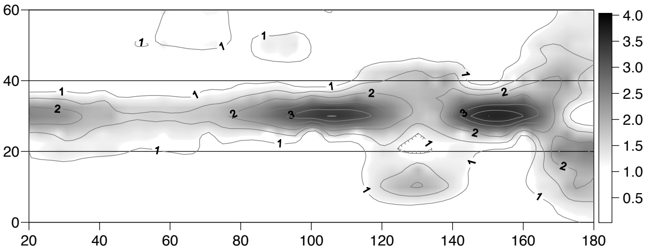


Fig. 9. Magnetogram m - $H_{n,z}$ of joint A, indications: 90 ~ 120 mm - SCZ, 140 ~ 170 mm - SCZ coincides with the location of the occurrence of the defects of the weld seam [32]

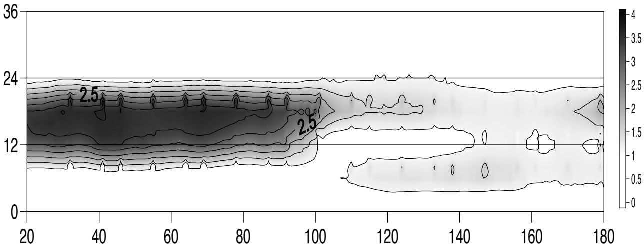


Fig. 10. Magnetogram m - $H_{t,x}$ of joint P12, indications: 20 ~ 110 mm - SCZ in the area of the weld seam coincides partly with the location of the occurrence of defects [33]

By finding stress concentration zones, the areas of potential or existing cracks can be found. It was found that the method of the MMM testing, apart from being applied to defect detection in weld seams, could be used to assess the level of residual stress, the quality of the thermal treatment after welding and to define the amount of delta ferrite in weld seams of austenitic steels (Figs. 10-12). The analysis of the changes in the RMF can also be used to assess the residual lifetime of weld seams [35,36]. Each of these applications requires an analysis of signals (the RMF components) with a view to developing criteria. The best way to develop such criteria is a combination of the results of experimental research and the results of the modelling of the RMF distributions [15].

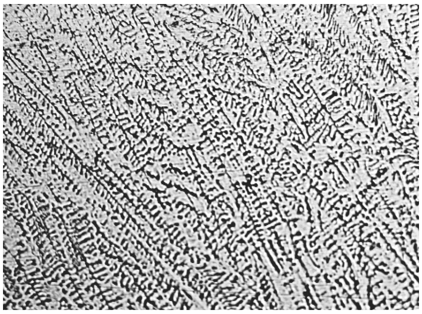


Fig.11. Joint P12 - 50 mm section - structure of the weld seam. Austenitic structure with a significant amount of interdendritic ferrite, etched with ferric chloride, magnification: 200x [33]

Fig.12. Joint P12 - 150 mm section - structure of the weld seam.Austenitic structure with narrow areas of interdendritic ferrite, etched with ferric chloride, magnification: 200x [33]

6. Application of the method of the metal magnetic memory testing in other industries

6.1. Diagnostics and assessment of the technical state of components of mining shaft hoists [37]

The latest revision of the operational health and safety regulations which are in force in underground mining widened the scope of requirements for the inspection of the technical state of machinery and equipment whose potential failure might pose hazard to human life or cause consequences of the technological disaster type.

The assessment of the technical state and the determination of the predicted time of safe operation (service life) of equipment should take into consideration, among others, an analysis (as of the day of the inspection) of the level of stress- and effort state of the main structural components of the equipment under examination. The base for the analysis to be conducted in a proper way should be the results of non-destructive testing obtained by means of all available inspection methods.

The use of the metal magnetic memory (MMM) method to assess the technical state of machinery and equipment operated in mining shaft hoists significantly increases the diagnostic potential of non-destructive testing in finding stress concentration zones and early detection of areas prone to fatigue cracks before the cracks actually appear.

6.2. Inspection of rails on a rail route [38,39]

The rails in the railway track are subject in a natural way to dynamic loads and therefore they are a favourable object to be diagnosed with the use of the magnetic memory method. The local concentrations of stress in the track rails in service are a perfect object for the application of the MMM method. The MMM method perfectly detects typical defects in rails and their joints: the horizontal cracks at the transition of the rail head and web, the horizontal crack in the neck of the thermite weld of the rail, the head checking defect, and surface defects resulting from the effect of the slippage of wheels. The head checking defect occurs on the inner side of the rail head at wheel-rail contact. It is characterized by fast development, typical of fatigue fractures. For this reason, a rail with this defect should be removed from the track quickly.

Unfortunately, its small depth in the first stage of development and its side location make it practically invisible to ultrasonic testing. However, it is very well detected by the MMM method. More and more dangerous are the surface defects resulting from the slippage of wheels, as they initiate cracks which advance into the rail. These cracks are invisible in ultrasonic testing (dead zone); due to the roughness of the rail surface, the heads lose acoustic contact.

7. Conclusions

The presented industrial applications of the metal magnetic memory method do not exhaust the topic of its use. The authors focused on the applications which are documented with publications. Additionally, the method is used in the power industry as an ancillary method for the inspection of pipelines, pressure vessels and the heating surfaces of boilers.

The metal magnetic memory method is a non-destructive testing method with a great potential and it is perfect for many applications. Unfortunately, many of its basic issues, such as the problems of its application procedures or the criteria of the evaluation of its indications still remain unsolved. In each case its application for a specific component calls for the development of a research methodology which takes into consideration the load state of the component during the examination, the values of the external magnetic field at the place where the examination is being carried out, as well as the location of the component. In the presented applications, the specialists using the method usually, through their own experience, work out the appropriate way of conducting tests and defining the evaluation criteria.

Research is currently being done on the examination of the residual magnetic field as a diagnostic signal for a reliable assessment of the state of the material. The expected results include the possibility to define the areas of plastic deformations in components, to determine an approximate distribution of stresses and deformations, and to define the residual life of components [40,41].

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