



## **Detection of local stress concentration zones in engineering components – the lacking link in the NDT system**

Anatoly A Dubov<sup>1</sup>, Peter Trampus<sup>2</sup>, Peter Ladanyi<sup>3</sup>

1 Energodiagnostika Co. Ltd., Russia, mail@energodiagnostika.ru

2 University of Dunaujvaros, Hungary, trampus@uniduna.hu

3 Interproject Europe Kft., Hungary, Peter.Ladanyi@tuv.net

### **Abstract**

It is known that the main sources of damage during operation of engineering components are local stress concentration zones (SCZs) that are formed under the action of workloads primarily on defects of metallurgical and process nature. Local SCZ is the local zone in a component where a significant deformation – compared to the mean deformation along the component volume – is present due to an unsuitable combination of component' features, structural heterogeneity and workloads. Sizes of these stress concentration zones vary from several tens of microns to several millimeters. Furthermore, it is unknown where these local areas are situated and how they can be detected. At the same time the reject norms of the applied NDT methods (ultrasonic testing, X-ray, MPI and other methods) at manufacturing plants significantly exceed the sizes of metallurgical defects. At present a fundamentally new NDT method based on the use of the magnetic memory of metal (MMM) is more and more commonly applied in practice. It uses the natural magnetization formed during the components' fabrication. The results are based on resent experiences. The article considers the capabilities of the MMM method during the diagnostics of metallurgical and process manufacturing defects in new components.

### **1. Introduction**

It is known that the main sources of damaging during engineering components operation are local stress concentration zones (SCZs) that form under the effect of working loads, first of all, on metallurgical and process defects.

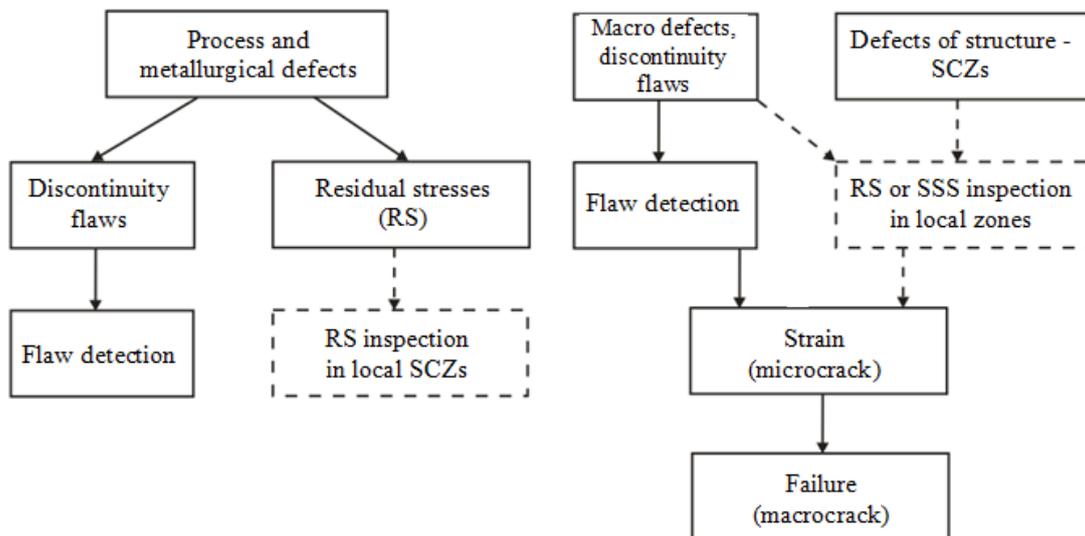
Metallurgical and process manufacturing defects are known to cause high level of residual stresses (RS) in local zones of the component. RS control at some productions is performed on a selective basis. In this case the average (volumetric) level of RS is inspected, and local RS zones due to internal defects of the metal, as a rule, are not inspected and omitted. Besides, the location of these local zones and the method of their detection are unknown.

As a rule, RS control during the incoming inspection is not performed. For these reasons, during the very first years of components operation under the working load their “rejection” takes place. Process and metallurgical defects, causing the high level of RS in local zones of components at unfavorable combinations with stresses due to working loads, cause accelerated development of damages.

It is known that conventional NDT methods – X-ray, ultrasonic testing, the eddy-current method, magnetic powder and dye penetrant inspection – are aimed at searching and detection of pronounced defects located primarily on the components' surface. Internal casting defects, various types of structural inhomogeneity as well as manufacturing process defects (welding, rolling, bending, heat treatment defects, etc.) remain undetected in components due to the lack of 100% quality inspection at most of the plants as well as due to imperfection of NDT methods applied. Moreover, these rejection standards of NDT methods used at products manufacturing plants are aimed at detection of defects with sizes that many times exceed those of metallurgical defects. For example, according to the norms of austenite pipes ultrasonic testing, the sizes of admissible defects do not exceed 25 mm in length and 0,3 mm in opening and depth. As practice shows, metallurgical defects of smaller sizes, when exposed to working loads, are the main sources of operational damages. In conditions of components operation practically all NDT methods are also aimed at detection of various-type discontinuity flaws with sizes significantly exceeding the size of defects that cause the development of damages.

Thus, it must be stated that the lack of RS inspection in order to detect stress concentrations on structural defects of components, both at manufacturing plants and during operation, is the lacking link in system of components NDT, which considerably reduces their safety and reliability.

Figure 1 shows the scheme of engineering components NDT arrangement that formed at present both at manufacturing plants and during operation. It can be seen in figure 1 that components inspection consists in the usual flaw detection without any assessment of stress concentration level on apparent (discontinuity flaws) and implicit (structural) defects. The lacking link in the NDT system is marked with a dotted line in figure 1.



**Figure 1. Block diagram of engineering components non-destructive testing at manufacturing plants and during operation**

## 2. Detection of local SCZs using metal magnetic memory method

The metal magnetic memory (MMM) method developed by Energodiagnostika Co. Ltd. (Moscow) becomes more practically implemented for solution of the problem of determination of local SCZs in new and operated components. Russian and International standards on the MMM method are published.

In accordance with ISO 24497-1:2007(E) “Non-destructive testing – Metal magnetic memory – Part 1: Vocabulary” the MMM method is a non-destructive testing method based on recording and analysis of distribution of self-magnetic leakage fields (SMLF) occurring on stress concentration zones (SCZs) and of structural inhomogeneity of components (SCZs are not only pre-known areas where the design features create different conditions for distribution of stresses caused by an external working load, but these are also randomly located areas, in which due to the initial metal heterogeneity combined with off-design additional workloads large strains occur). In this case SMLF reflect the irreversible variation of magnetization in the direction of the effect of maximal stresses due to working (external) loads, as well as structural and process history of components and welded joints after their fabrication and cooling in the magnetic field of the earth.

The MMM method differs fundamentally from all known magnetic NDT methods by the fact that its application does not require artificial magnetization of the component, but it uses the natural magnetization and aftereffect that appears in the form of the magnetic memory of metal related to actual strains and structural changes.

The MMM method requires no preparatory works during the inspection and differs from other NDT methods by the fact that it indicates the level of stress concentration, i.e. it indicates the degree of the detected defects' hazard.

During the industrial investigations it was also established that the magnetic memory of the metal on new ferromagnetic engineering components reflects their structural and process history.

Melting, forging, forming, heat treatment and welding are performed at metal temperatures significantly exceeding the Curie point (for iron-based alloys - approximately 760-770°C), when the residual magnetization disappears. During subsequent metal cooling at the time of passing through the Curie point ( $T_C$ ), when the magnetic permeability  $\mu$  is maximum, components gain a high level of residual magnetization  $M_{res}$  even in a weak external magnetic field of the earth or a workshop (see figure 2).

As a result of this process, at which the energy of crystallization and thermal stress (external layers of components cool faster than internal) is by order higher than the external magnetic field energy, the residual magnetization distribution in components by magnitude and direction is determined by the component's shape, its structural and process inhomogeneity. Thus, the structural and process history of the components metal due to the cooling process appears in the form of natural magnetization (magnetic memory of metal).

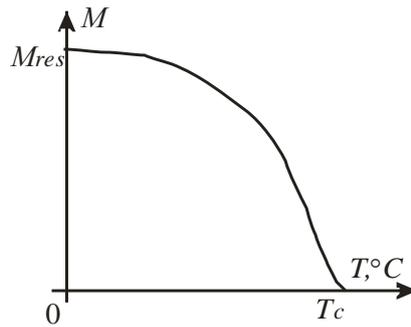


Figure 2. Schematic variation of ferromagnetic's magnetization ( $M$ ) depending on the temperature:  $T_C$  – Curie point temperature ( $768^\circ\text{C}$  for Fe)

### 3. Inspection results

Let us further consider the MMM method's capabilities at diagnostics of new and operated components in order to detect local SCZs – the sources of damages development.

Figure 3 shows the inspection results of a new  $\varnothing 22$  mm (St.05Cr16Ni4Cu2BT13) rod used for fabrication of the shaft of electrical centrifugal pump (ECP) manufactured at LLC "PC Borets" production works (Lebedyan).

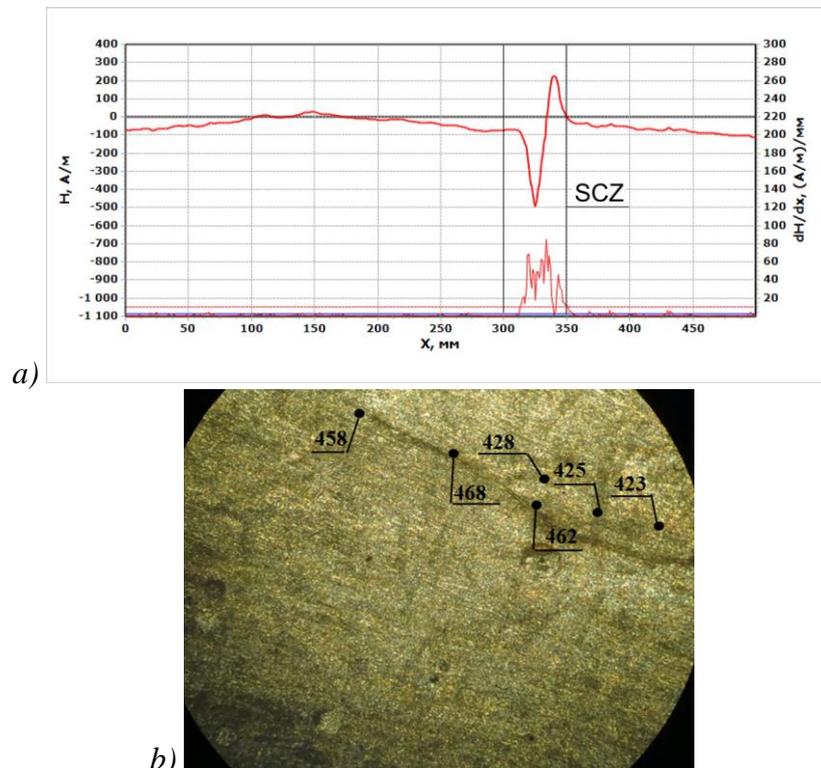
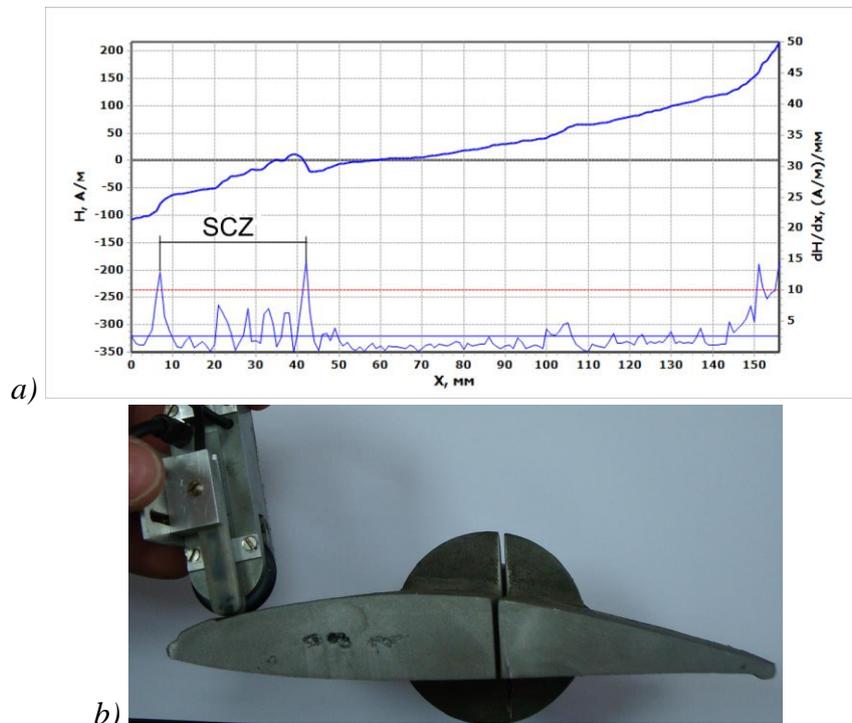


Figure 3. Inspection results of a new  $\varnothing 22$  mm (St.05Cr16Ni4Cu2BT13) rod used for fabrication of the shaft of electrical centrifugal pump (ECP): *a* – distribution magnetogram of the normal component of the self-magnetic leakage field  $H_p$  and its gradient  $dH/dx$  recorded in the SCZ; *b* – metal's structural state of the rod #2204 in the section that coincides with the SCZ

Figure 3, *a* shows the distribution magnetogram of the normal component of the self-magnetic leakage field  $H_p$  and its gradient  $dH/dx$  recorded in the stress concentration zone (SCZ) during scanning with the instrument sensor along one of the generating lines of the rod #2204.

Figure 3, *b* shows the metal's structural state of the rod #2204 in the section that coincides with the SCZ. Figures indicate the micro hardness values along the line of a metallurgical defect and outside it.

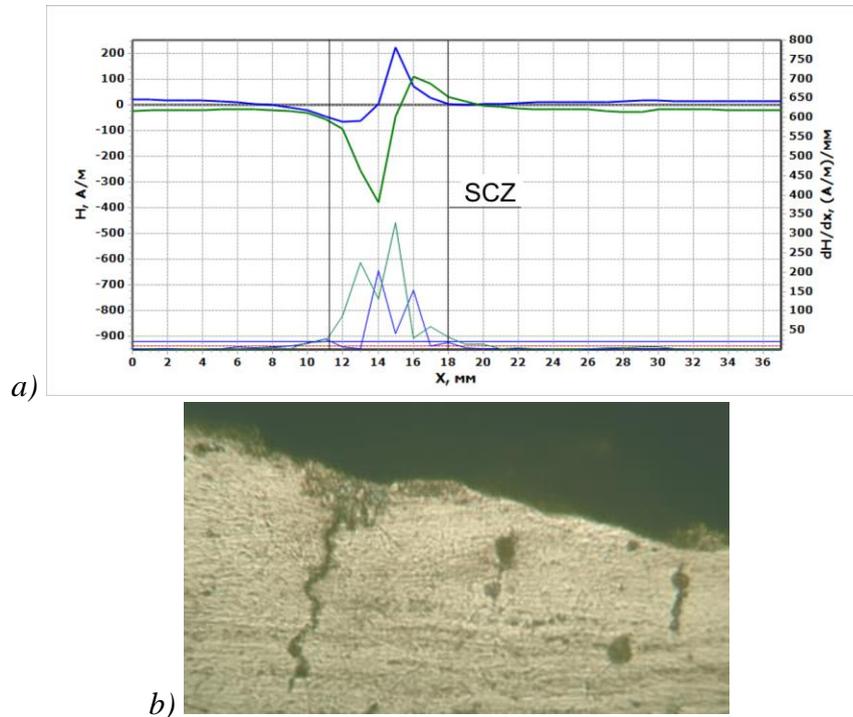
Figure 4 presents the results of inspection by the MMM method of a new hydraulic turbine blade. Figure 4, *a* shows the distribution of the magnetic field  $H_p$  and its gradient  $dH/dx$  recorded during the inspection along the external surface of the blade. SCZ characterized by local variations of the field gradient is indicated in the bottom part of the magnetogram. Figure 4, *b* shows casting defects detected in the metal depth after cutting of the blade opposite the SCZ recorded by the MMM method on the external surface.



**Figure 4. Results of inspection by the MMM method of a new hydraulic turbine blade:**  
*a* – distribution of the magnetic field  $H$  and its gradient  $dH/dx$  recorded during the inspection along the external surface of the blade;  
*b* – casting defects detected in the metal depth after cutting of the blade

Figure 5 presents the results of inspection by the MMM method of a  $\varnothing 42 \times 7$  mm pipe of steel 10Cr13G12BS2Ni2Cu2 cut out of the new power boiler platen superheater. Figure 5, *a* shows the distribution magnetogram of the self-magnetic leakage field  $H$  and its gradient  $dH/dx$  recorded in the SCZ on one of the pipe generating lines. Despite the fact that this pipe was fabricated of stainless steel that should be practically non-magnetic in the initial (as-fabricated) state, however, a ferrite phase, recorded during the inspection by the MMM method as a magnetic anomaly, formed in the local zone due to

violations of its manufacturing technology. Figure 5, *b* shows the cracks detected on the internal surface of the pipe cut out from the zone of the magnetic anomaly that corresponds to the SCZ.



**Figure 5. Results of inspection by the MMM method of a  $\text{Ø}42 \times 7$  mm pipe of steel 10Cr13G12BS2Ni2Cu2 cut out of the new power boiler platen superheater: *a* – distribution of the SMLF  $H$  and its gradient  $dH/dx$  recorded in the SCZ; *b* – cracks detected on the internal surface of the pipe cut out from the SCZ**

The presented in figures 3, 4 and 5 examples from the practice of the MMM method application on new components of various productions clearly demonstrate general drawbacks in organization of NDT at manufacturing plants. All the above-mentioned components were tested by the NDT system currently existing at plants. However, as it was noted above, at present most of the manufacturing plants lack the inspection for detection of metal defects beyond the standardized sensitivity limits of the applied inspection methods and means. Application of the MMM method, which reveals metallurgical and technological production defects in the form of magnetic anomalies corresponding to local stress concentration zones, would allow to ensure the 100% components inspection even in mass production.

During operation of engineering components the major sources of damages development are also local SCZs, the formation sites of which are practically impossible to predict by calculation methods. Application of the MMM method offers a unique opportunity to detect the local zones with maximum stress concentration at an early stage by means of performance of the 100% inspection of various equipment units.

For classification of magnetic anomalies, characterizing SCZs by the degree of their hazard in accordance with the technique described in (1), a comparison of all magnetic anomalies detected on a specific unit by the field gradient  $dH/dx$  value is performed.

For the same-type equipment units, based on the laboratory and industrial investigations, the limiting value of the field gradient is determined, at which a microcrack is formed and the damage development starts.

In accordance with the definitions presented in paper (2), the physical sense of the magnetic parameter  $dH/dx$  is that it reflects concentration (or density) of the magnetic energy in the component's volume conditioned by the strain energy density.

#### **4. Conclusions**

The considered example of the MMM method application for detection of the local SCZ at an early stage of the damage development clearly demonstrates the significance and efficiency of its application in combination with other NDT methods. The experience of the MMM method application on different equipment under long-term operation in various industries shows that only 5 to 10% of the total metal volume reaches the limiting state (physical ultimate strength) and achieve the stage of damage development. Unfortunately, it is practically impossible to determine these local SCZs – the sources of damages development – by calculation methods. Such problem can be solved using the methods of early diagnostics (the MMM and AE methods).

During the analysis of components fracture mechanism determination of local zone dimensions (volume, area, length), at which the limiting state of the metal and the component itself occurs, is the most valuable. Exactly this challenge, that has so far been the subject of study on specimens in fracture mechanics, is solved using the MMM method directly on the equipment during the diagnostics of various units' condition.

#### **References and footnotes**

1. AA Dubov, AIA Dubov, SM Kolokolnikov, "The metal magnetic memory method and inspection instruments: Training handbook", Moscow: "Spectr" Publishing House, 2012, 395 p.
2. VT Vlasov, AA Dubov, "Physical theory of the "strain - failure" process - Part I: Physical criteria of the metal's limiting states", Moscow: ZAO "Tisso", 2007, 517 p.