Development of references of anomalies detection on P91 material using Self-Magnetic Leakage Field (SMLF) technique

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Abstract. This technical paper demonstrates the successful of the application of self-magnetic leakage field (SMLF) technique in detecting anomalies in weldment of a thick P91 materials joint (1 inch thickness). Boiler components such as boiler tubes, stub boiler at penthouse and energy piping such as hot reheat pipe (HRP) and H-balance energy piping to turbine are made of P91 material. P91 is ferromagnetic material, therefore the technique of self-magnetic leakage field (SMLF) is applicable for P91 in detecting anomalies within material (internal defects). The technique is categorized under non-destructive technique (NDT). It is the second passive method after acoustic emission (AE), at which the information on structures radiation (magnetic field and energy waves) is used. The measured magnetic leakage field of a product or component is a magnetic leakage field occurring on the component’s surface in the zone of dislocation stable slipbands under the influence of operational (in-service) or residual stresses or in zones of maximum inhomogeneity of metal structure in new products or components. Inter-granular and trans-granular cracks, inclusion, void, cavity and corrosion are considered types of inhomogeneity and discontinuity in material where obviously the output of magnetic leakage field will be shown when using this technique. The technique does not required surface preparation for the component to be inspected. This technique is contact-type inspection, which means the sensor has to touch or in-contact to the component’s surface during inspection. The results of application of SMLF technique on the developed P91 reference blocks have demonstrated that the technique is practical to be used for anomaly inspection and detection as well as identification of anomalies’ location. The evaluation of this passive self-magnetic leakage field (SMLF) technique has been verified by other conventional non-destructive tests (NDTs) on the reference blocks where simulated defects/anomalies have been developed inside at the weldment. The results from the inspection test showed that the signatures of magnetic leakage field gradient distribution prove that the peak is found on the location of defect/anomaly in the reference block. It is in agreement with the evidence of anomaly that seen in the radiography test film (RT).

1. Introduction

A passive self-magnetic leakage field (SMLF) technique is a technique that use natural magnetization and the after displayed results as the magnetic memory of metal to actual strains and structural changes in products and equipment metal. It is quick detection of the stress concentration zones (SCZs) based on 100% inspection of equipment and structures. The SCZ is defined as the zone with high stress-strained state inhomogeneity [1]. The SCZs are the main sources of equipment damages. Degradation of mechanical properties, corrosion, fatigue, creeping are developed in the SCZs most
intensively [2]. Hence, detection of the SCZs is very important for early diagnostics of fatigue damage and evaluation of equipment and structure lifetime. SMLF technique is non-destructive testing (NDT) method based on analysis of self-magnetic leakage fields (SMLF) distribution on component’s surfaces for determination of stress concentration zones (SCZs), imperfections, and heterogeneity in microstructure of the material and in welded joints [3]. This method is deemed as passive technique because it uses natural magnetization and no any artificial magnetization used. Its equipment is very simple and portable (hand-held equipment). It has fluxgate transducers that have to in-contact with surface of component during inspection. Fluxgate transducers are usually equipped with two coils: excitation coil and pick-off coil (see Figure 1). These coils usually have a core (wire-shaped, toroid, oval, etc.). The basic property of fluxgate sensor is that the sensor core is periodically saturated by the excitation current and that its output is on the second harmonic (or higher even harmonic) of the excitation frequency. Harmonic (sinusoidal or pulsed) voltage will apply on exciting coil. In case of external field absence similar harmonic (sinusoidal or pulsed) voltage will be measured on measurement coil. The second harmonic (doubled frequency) will appear when fluxgate subjected by external field. Voltage of the second harmonic will be filtered out and measured.

![Figure 1. Schematic of working principal of SMLF technique.](image)

This method is the only passive method among the magnetic NDT methods. The method allows detecting SCZs and locations of defects by using the pattern of SMLF and its gradient distribution. The basic task of testing by using this method is assessment of test object stressed state with SCZ detection at simultaneous determination of defects locations. The advantages of this method are: small-sized instruments are used for the testing (e.g. for boiler tube inspection, it enables the scanning device/sensor to reach at the inspection spot which has limited space for accessibility of the normal sensors (e.g. in between of stubs), not required any special test surface preparation, not required special magnetization, the method allows carrying out quick testing of components made of carbon, ferritic, pearlitic and austenitic steel grades and last but not least, the technique allows carrying out quick quality testing.

The output from the measurement that fundamentally from SMLF is actually considered as after-effect result which occurs as residual magnetization in components and welded joints formed in the course of their fabrication and due to irreversible change of the local magnetization state of components in zones of stress concentration and damage under working [3] (see Figure 2). SMLF method has been demonstrated its capability to assess material conditions or properties such as residual stress and SCZs measurement which both can be used to assess material integrity or strength. Therefore, it is a basis to be used as after-effect metal magnetic memory measurement and assessment for material or component. Figure 2 shows physical fundamental or condition based of stressed material that associated with “metal magnetic memory (MMM)”; it is about the measurement of magnetic field scattering that by structural and mechanical heterogeneities at metal natural magnetization. Figure 2 explains that a very specific feature of the method, in which MMM method is distinguished from other NDT methods, is that it detects concentration of stresses on defects. Based on this basis, an equipment called Metal Magnetic Memory (MMM) technology which attributed by SMLF technique has been developed by Energodiagnostika, Russia. Bin et al, (2012) used MMM technology for detection of fatigue fracture on diesel engine crankshaft [4]. They found that MMM
technology can be applied to ferromagnetic components such as diesel engine crankshaft in daily routine to dynamic monitor crack failure of crankshaft. Significantly, they found that MMM technology is capable to monitor and give indication for early warn on early fatigue and this can be as a tool to provide solutions to prevent serious accidents.

**Figure 2.** Interrelation between SMLF distribution and magnetic domain structure

SMLF is a self-magnetic leakage field occurring on the component’s surface in the zones of stable lines of dislocations under operational or residual stresses or in the zones of maximal heterogeneity of metal structure [3]. The technique has unique opportunity to carry out integral assessment of the weld’s actual state taking into account structural inhomogeneity, distribution of residual stresses and welding defects. Wenjian et al. [5] has proved the effective of MMM testing for early damage diagnosis of ferromagnetic materials. They found that magnetic domain structure’s characteristic changes with the change of external loads. It was demonstrated that the magnetic flux leakage signal of specimen surface increases with the external loads increases. This shows the technique is reliable, effective and has basis for further study of the microscopic mechanism of ferromagnetic materials magnetic memory testing.

The comparison of measurement parameters of magnetic fields; Magnetic field intensity (H) and Magnetic Field Gradient distribution (dH/dx) has been done by Wang et al. [6]. In their experimental work, the Hp(y) value and Hp(y) gradient dHp(y)/dx of the middle point of the sample were measured using MMM testing instrument. They found that from the Hp(y) value plot, Hp(y) value was around zero with the applied tensile stress. While, dHp(y)/dx gradient has a good linear relationship with applied tensile stress. However, dHp(y)/dx value showed arbitrary change with the applied stress.

Jiancheng et al. [7] has used MMM method where SMLF technique was applied to detect stress concentration and defining critical stress state that leading to structural damage. They used the technique to evaluate the stress concentration quantitatively due to ambiguous physical mechanism. They demonstrated that the technique has potential to detect early defects in ferromagnetic materials. In their experiment they used mild steel (Q235) defective specimens in demagnetization state were loaded in tension up to visible necking, with magnetic memory signals measurement made at increasing stress levels. They found that in the plastic stage, an abnormal wave occurred in the stress concentration zone and its height value was sensitive to plastic deformation levels. Different magnetic signal characteristics in the plastic-plastic region indicate that the magnetic memory method can identify macro-yielding and early damage. This detection and indication is of profound significance for ensuring safe operation of equipment in service. Their findings show that the Hy signals show different variations in elastic and plastic regions due to the influence of either applied stresses or different deformation levels. They concluded that the abnormal wave in Hy signal observed in the plastic stage can detect the critical state of the macroscopic yield point.

Dubov [8] has used MMM method to investigate of the actual stress states in the hoisting vessel bearing rods as an alternative for other methods within the scope of diagnostics and reliability prediction of hoisting vessel structure during operation. This method were used for precise detection of the location of stress concentration zones that representing the main sources of fatigue damages development, determination of the maximum fatigue stress state of the bearing rods relative to the mechanical properties of the material. This is including of detection of the existing cracks and
estimation of the assumed non-failure operation time (lifetime) of the bearing rods. Dubov [8] concluded that MMM method can be used for early diagnostics of fatigue damages (cracks) of bearing rod. This demonstrates that SMLF technique that principally used in MMM method is capable for determination for the investigated rod of the actual fatigue stress state and estimation of the assumed non-failure operation time of bearing rods.

The MMM method is a non-destructive testing method with a great potential and it can be adopted for many applications in inspection and material assessment. However, 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 [9]. This is a justification for research of using this technique as a tool for material integrity assessment. In most presented application, Roskosz et al. [9] commented that the specialists using the MMM method usually, through their own experience, work out the appropriate way of conducting tests and defining the evaluation criteria. Therefore, this technical paper is meant for providing references on the SMLF signatures or output obtained based on the known defects types, parameters and location that specifically developed in the sample blocks.

2. Methodology

The aim of the project is to verify the application of SMLF with the known type of simulated defects in weldment, size and location. The simulated defects in the weldment on a thick P91 material blocks (thickness 1 inch) were developed for the project of verification SMLF technique on MMM method in detecting defects within material. The blocks are called “reference blocks”. 3 types of defect were developed for this purpose; voids, cavity and crack. Basically, the simulated defects developed in the material P91 have difference length sizes, but the height is the same, e.g crack height is 2.5 mm (see Figure 3). The summary of simulated defects in the reference block is shown in Table 1. The defects were checked and verified with other NDT techniques; Ultrasound test (UT), Dye Penetrant test (DP), Magnetic Particle test (MP, Phase Array Ultrasonic Test (PAUT) and Radiography test (RT). The measurement or inspection results using SMLF technique was compared with the abovementioned techniques.

![Figure 3. Simulated defect of linear crack 10mm in weldment as depicted in blue print in above drawing. X position of defect location is 47 mm, depth of defect from surface is 19 mm.](image-url)
Table 1. Summary of simulated defects manufactured and conventional NDTs tested by Flawtech.

| Anomaly Type | Flaw parameter | Definition |
|--------------|----------------|------------|
| Porosity     | 1) Cluster 10mm porosity, Depth 1/4 depth (6mm)  
               2) Cluster 20mm porosity, Depth 1/2 depth (12mm)  
               3) Cluster 30mm porosity, Depth 3/4 depth (19mm) | Porosity is gas pores found in the solidified weld bead.  
                                                   Pores may vary in size and are generally distributed in random manner. |
| Cavity       | 1) 10mm cavity, Depth 1/4 depth (6mm)  
               2) 20mm cavity, Depth 1/2 depth (13mm)  
               3) 30mm cavity, Depth 3/4 depth (19mm) | Hole(s) in weld  
                                                   Discontinuity formed by gas entrapment during solidification |
| Crack        | Linear Crack | Also called as discontinuity.  
               Discontinuity is defined as an interruption of the typical structure of a material |

In evaluating the accuracy of SMF technique in detecting anomalies in weldment, a pipe T-joint reference has been fabricated which contains of 3 cracks at difference locations as can be seen in Figure 4. The thickness of the pipe is 1 inch.

![Thickness: 1 inch](image)

**Figure 4.** Simulated defect of linear cracks at 3 different locations in the weldment of T-joint P91 pipes as shown in the product drawing in above picture.
Figure 5. Calibration of scanning device (sensor) and its functionality checking: vertical down sensor’s position (Left). Flux-gate transducers in two-component sensor (Right).

For SMLF measurement, tester equipment and scanning device (sensor) type TSC-3M-12 (Energodiagnostika) and 2M were used. Figure 5 shows the equipment is positioned during sensor calibration and functional checking process. The reading of H2 and H4 (even sensor numbers) are normal components (Hp) of SMLF gradient, while the reading at odd sensor numbers (H1 and H3) are the tangential components of SMLF (see Figure 5-Right). Scanning device type 2M has 2 sensors. Sensor 1 has tangential and normal components of SMLF gradient H1 and H2 respectively. While sensor 2, the tangential and normal component of SMLF gradient are indicated by H3 and H4. During the calibration process, as shown in Figure 6, the readings of normal component of SMLF gradient at vertical down sensor position for sensor 1 and 2 show the reading difference for H2 (sensor 1) and H4 (sensor 2) is 2 (A/M)/mm. Similarly, the reading difference of H1 (sensor 1) and H3 (sensor 2) shows close reading, 2 (A/M)/mm. These show the scanning devices (sensors 1 and 2) are in good condition. For this verification and assessment work of the application of SMLF technique on a thick component/sample, the reading of normal component of SMLF on the surface of component/sample was taken into consideration for assessing defect. Figure 7 show a base-line reading of SMLF at the surface of reference block on the position of non-defect (good condition). The average of reading recorded for tangential component of SMLF gradient is about 138 (A/M)/mm.

Figure 6. Scanning device (sensor) in-touching with P91 reference block’s surface at non-defect location.
In this verification project on the SMLF technique, the developed reference blocks have defects with various depths from surface, as can be seen the summary of defect types and parameters in Table 1. The capability of the SMLF technique was studied for any significant different results for various depths of defect in the blocks. Commonly, the threshold used in determining defect or critical condition of defect in weldment is 10 (A/M/mm). In this work, if the output (signature) of SMLF is over the threshold, hence, we confirmed that the defect is identified at the location where the scanning device is positioned on the surface of component/reference block during the inspection. The scanning device of the system has length decoder (roller), therefore the length of the sensor travels is shown on the output/result and the defect location which based on the peak over the threshold can be determined accurately. Human error for this inspection is about ±3 mm. The measurement of normal component of SMLF gradient performed on the surface where the known anomaly type and location will be discussed in details on results section.

3. Results and discussion
Magnetic particle (MP) test is unable to detect subsurface anomaly. Similarly, DP test only applicable for surface defect detection. Internal defect can be clearly shown by RT, however RT has limitation where its equipment is expensive, it needs high level of skill and it has obvious limitation on the weldment features such as fillet pipe joint. In addition, accessibility for the RT equipment to be used at limited space such as in between of stubs in power plants is an issues and limitation of RT.

Figure 7. Scanning direction of the reference block’s weldment.

Figure 8. Comparison of Radiography Test (RT) and SMLF results on the sample block #018, linear-crack 10 mm at depth 19 mm from surface: showing the location of defect is found in agreement for both technique RT and SMLF.
Figure 8 shows the agreement of results between RT and SMLF technique. It shows that SMLF technique detected the anomaly exactly at the location as indicated by RT. The scale in the Figure 8 shows the defect is located at 47mm from the edge (see Figure 8-top). The signature of normal component of SMLF gradient is above the threshold 10 (A/M)/mm. It is noted that as can be seen in Figure 8, SMLF output has edge effect. The edge effect is attributed by cutting process at the edge of the block during fabrication process. The secondary process such as cutting has caused the residual stress and this stress remains in the material. It is found that the signature of SMLF gradient is in “U” shape. The higher SMLF gradient at the beginning and end of the measurement is due to the edge effect where the scanning device was started and ended at the edges of the reference block. It is demonstrated that the edge effect length is about 32mm from the edge. However, the peak that over the threshold at the middle/centre of output length is attributed to the known defect at the centre (about 47 mm from the edge-datum).

Table 2. Reference on SMLF signature (curve and spike).
The summary of SMLF gradient results and its signature/pattern distribution according to the type of defects is shown in Table 2. The result shows obvious shape different with the different types of anomaly. Significantly the output shows single sharp peak with very high amplitude when the scanning device passed the crack compared to porosity and cavity. The gradient of SMLF on normal component (Hpy) (in this study, refer to 1 sensor), the output of SMLF for porosity defect shows many spikes with much closed legs, while for cavity defect it shows single spike with wide opening “floating” leg. Planar-crack can be differentiate with linear crack, it was demonstrated that planar crack has the output of SMLF signature with single spike above the threshold with the characteristic of wide opening leg floating for certain length before it falls back to the floor/axis (Table 2-planar crack). It is coincident with the sensor moves along the crack, which is the reason the signature has wide opening leg (right) before it falls back to the floor/axis when the scanning device has over the defect length.

Refer to the blue print of graphical drawing as can be seen in Figure 4 (top), the results as shown in Figure 10 demonstrates that SMLF technique is capable of scanning, detecting and identifying the type of crack. The results of SMLF scanning obviously detects 3 significant peaks at different locations. The results of SMLF inspection is in agreement with the blue print in the drawing. The output show very sharp spike with very high amplitude, thus easily the NDT technician can define the type of anomaly inspected is linear crack. This can be confirmed and referred the signature pattern to the Table 2; very sharp peak with high amplitude over the threshold, then the defect type must a linear (transverse) crack. Figure 9 demonstrates that depth of defect from the surface does not contribute to significant different of amplitude of the peak. Obviously for crack type of anomaly, as can be seen in Figure 9, the shape where sharp single spike is similar for the 3 cracks that developed in the reference P91 pipe-joint (see the output in Figure 10).

4. Conclusions
The main purpose of the application of this technique is the determination of stress concentration zones (SCZs) and simultaneously identification of defect in ferromagnetic materials. The validation works on the developed reference blocks have demonstrated that SMLF technique can detect internal defects in ferromagnetic material P91. It also demonstrated that SMLF technique can detect flaws/defects in a thick ferromagnetic material. The SMLF technique can identify the location of defect with the accuracy ±3 mm. Based on the signatures of SMLF output of its gradient, the type of
anomaly within the material can be determined. Comparatively. The SMLF technique is practical, save cost, faster and can be done via automation with special design of scanning device, compared with other NDTs such as Dye Penetrant, Magnetic Particle, Ultrasonic and Radiography tests.

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