Grzegorz PSUJ, Barbara SZYMANIK

West Pomeranian University of Technology, Szczecin

doi:10.15199/48.2016.05.02

Fatigue Monitoring of Steel Structures using Electromagnetic and Infrared Thermography Inspection Methods

***Abstract**. Two nondestructive methods are used for monitoring of fatigue process in steel samples under cyclic loading: the infrared thermography (IRT) and electromagnetic (EM). The IRT allows to observe the general global condition of the material while the EM to carry out local, detail examination of the fatigue stage in critical region. Both methods have different physical basics what allows to obtain a wider range of information about the state of the structure.*

***Streszczenie.** W pracy wykorzystano dwie nieniszczące metody badań do monitorowania procesu zmęczeniowego stalowych próbek poddanych obciążeniom cyklicznym: metodę termografii podczerwonej (IRT)j i elektromagnetyczną (EM). Metoda IRT umożliwia obserwację globalnego stanu badanego materiału natomiast metoda EM pozwala na dokładną lokalną inspekcję stanu zmęczeniowego obszarów krytycznych. Z uwagi na fakt wykorzystywania odmiennych właściwości fizycznych do pośredniej obserwacji stanu struktury przez obie metody możliwe jest uzyskanie szerszego zakresu komplementarnych informacji o zmianach zmęczeniowych. **Dwie nieniszczące metody badań do monitorowania procesu zmęczeniowego stalowych próbek poddanych obciążeniom cyklicznym**:*

Keywords: fatigue evaluation, electromagnetic nondestructive evaluation, infrared inspection.
Słowa kluczowe: ocena stanu zmęczeniowego, nieniszcząca elektromagnetyczna ocena, inspekcja podczerwona.

Introduction

Assessment of a structure fatigue life depends on many factors such as stress history, environmental conditions and initial material characteristics i.e. fracture toughness, critical load or tensile strength. The estimation of fatigue failure risk requires to carry out the analysis and prediction algorithms taking into consideration initial strength capacity, production technology and types of possible flaws introduced during production or operation period [1]. The process requires also determination of local condition of a material, which involves evaluation of its microstructure, applied and residual stress values in accordance to strain state as well as crack grow area within the examined region. Therefore, the need for application of nondestructive testing and evaluation methods contributing the process of determining the state of stress and damage in the material emerges [1, 2]. Some of the most commonly used techniques are: visual, penetrant, ultrasonic, acoustic, radiographic and electromagnetic. The purpose of the paper is to present and compare results of fatigue monitoring carried out by electromagnetic and infrared thermography method.

Inspection methodology

During the selection of nondestructive testing methods contributing to the process of assessing the degradation state of the material several factors must be taken into account. It is important to analyze what type of defects may occur in the examined construction together with the capability of the NDT technique to distinguish between the areas having the flaws and without them. Furthermore, the possibility of carrying out a rapid assessment of the overall condition of the structure as well as obtaining detail information for the selected critical areas has to be also considered. Therefore in this paper two nondestructive testing methods are used to monitor the progress of fatigue process in steel samples: the electromagnetic for local and detail examination of crucial region and the infrared allowing estimation of the general condition state of tested material.

Due to the electromagnetic properties of steels utilized for the constructions, the use of the electromagnetic testing methods becomes a natural solution for evaluation of theirs damage stage. Material properties are influenced by the stress and fatigue loading conditions. It is known that microstructure features affect the magnetic one [2]. Therefore, by monitoring changes of magnetic properties, the damage state of the material can be evaluated. Various magnetic properties can be considered in the process of damage state evaluation [2, 3]. Hysteresis loop parameters such as remanence or coercivity as well as Barkhausen noise (BN) characteristic values such as signal's energy shows good correlation with the damage state of the material. In the recent times the increased importance of thermographic method may be also observed. The active infrared thermography is one of the methods that are widely used in the nondestructive testing of materials [4]. Internal structure of the tested material, in particular defects (such as cracks or weakening of the structure caused by the mechanical stress) affect the free flow of heat. A sensitive infrared camera is used to observe the temperature distribution over the sample's surface. The high temperature resolution allows to observe even small internal inhomogeneities in the form of the overheated or colder places, showing the location, size and type of defects. In the global assessment the most important is that the infrared camera with a high resolution allows the simultaneous observation of relatively large areas. The observation allows the initial location of the areas where the material is subjected to higher loads. Another advantage of this method is the ability to quickly inspect the materials due to the fact that the ferromagnetic materials have generally a high thermal conductivity coefficient. After preliminary location of the areas susceptible to damage, the thermal camera with a micro lens can be used for the final, local assessment of the steel structure.

Measuring system and methods

Measurements were carried out using a computerized universal NDT system (Fig.1.). The system contains of two main subsystems: a fatigue stress unit (FSM) and a nondestructive inspection one. In order to proceed the cyclic loading tests, a hydraulic type machine (1) was used. In case of nondestructive subsystem two modes were utilized: the electromagnetic (EM) and the infrared thermographic (IRT) .

In order to monitor changes of the electromagnetic properties a transducer (2) allowing BN observation was used. The transducer (Fig. 2) consists of excitation coil and two pick-up coils. The excitation coil is wound on the C-shaped ferrite core. The first pick-up coil was placed directly in the neighborhood of the specimen surface measuring signal correlated both with the structure state of the tested material and interfering noises. The second one was placed above in the optimized distance, so that it measured only unwanted interfering signals. Both pick-up coils were connected differentially, which allowed for minimization of unwanted field influences on the measuring signal. The transducer was covered by a ferromagnetic shielding box. The excitation coil was driven by a 30 Hz sinusoidal current. Before A/D conversion the measured signals were amplified and bandpass filtered using Krohn-hite 3988 dual channel programmable active filter. The details of the EM subsystem and transducer can be found in [5].

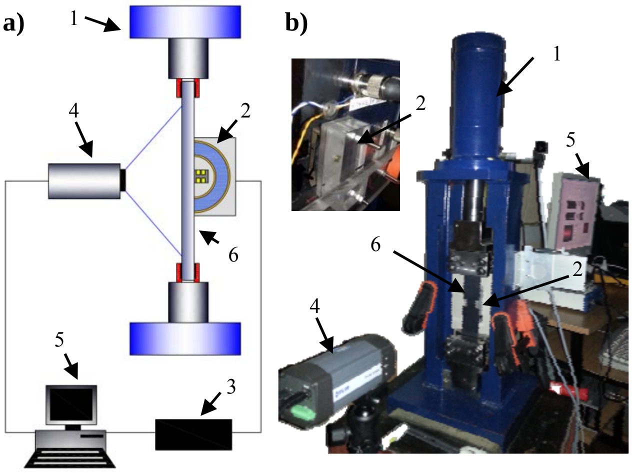

Fig. 1. Measuring system: a) schematic diagram, b) photo; 1 – fatigue stress machine, 2 – electromagnetic transducer, 3 – electromagnetic excitation and pickup subsystem, 4 – Infrared camera, 5 – PC controlling and acquisitioning computer, 6 – steel sample.

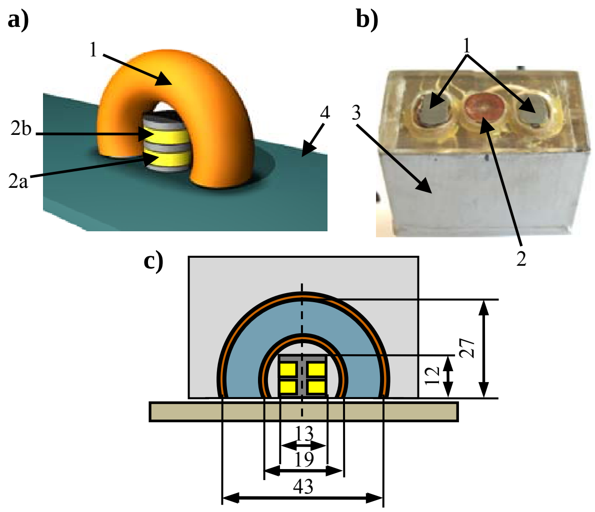

Fig. 2. Barkhausen noise transducer: three-dimensional view (a) , photo (b) and cross-section view with dimensions (c) of the transducer; 1 – ferrite core, 2a- main pick-up coil, 2b – reference pick-up coil, 3 – shielding, 4 – examined sample.

The temperature changes of the examined sample were observed by the infrared camera FLIR A325 (4). The camera has the temperature resolution up to 0.05 °C and is able to record 60 thermograms per second.

In order to synchronize operation, both subsystems were managed and controlled by a PC class computer (5) equipped with data acquisition boards NI 6221 and NI 6251 using a dedicated software implemented in the LabVIEW environment.

All experiments were carried out for planar specimens made of low carbon construction steel St3s (PN-88 H-84020). The shape and dimensions as well as photo of the samples are presented in Fig. 3. During the experiments the samples were loaded in a longitudinal direction using a cyclic loading machine. The maximum loading strength was set to 380 MPa. In the initial phase of the loading process the samples were subjected to a preliminary tension using the constant stress value of 220 MPa. In the next stage an alternating cycling loading of frequency equal to 4 Hz was superimposed to the offset value. In order to initiate the fatigue crack grow in the selected part of the sample, a notch of 1 mm length was made on one side of the sample in the central part of region of interest (ROI). The data acquisition was carried out in periods. Every 240 fatigue cycles both BN signals and IRT camera images were collected and stored. The total number of fatigue cycles obtained during experiments were close to $2 \cdot 10^5$.

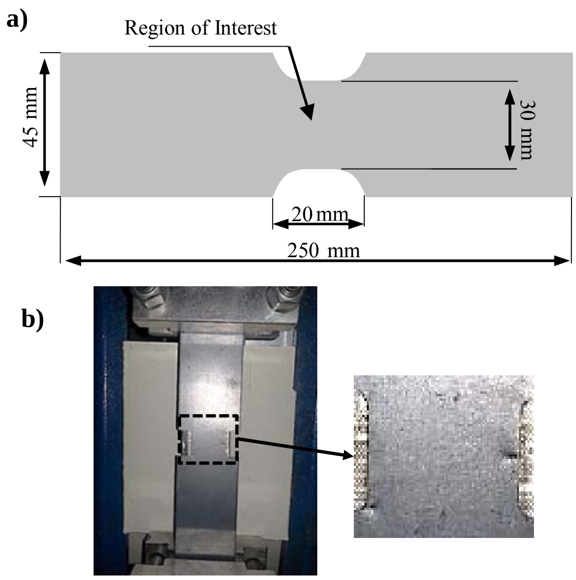

Fig. 3. View of fatigue loaded steel samples: a) draw with the shape and size of the samples, b) photo of the sample under fatigue test with enlargement of depicted (by black rectangle) region of interest.

Signal processing

In case of the BN, first several features were extracted directly from BN signal. The analysis of characteristic values as well as statistical ones was proceeded. As a result, parameters such as standard deviation, variance or energy were obtained. Next, the envelope of BN signals was computed. The moving window median filtration was applied in order to get the BN signal profile. Then the 5th order polynomial was fitted to achieve the BN envelope. Finally, the features such as envelope's peaks value, position or width were calculated.

In case of the IRT, the obtained thermograms sequence was analysed by comparing the temperature values from two chosen regions: the sound region and the region of interest (shown in Fig. 4). First all the thermograms in the sequence were normalised by subtracting the computed mean value thermogram. This procedure allows to remove the temperature background. The maximum and standard deviation values were compared for both regions. Moreover the IR thermography gives also the possibility to visualize the temperature distribution directly at the sample's surface. The sequence of thermograms was processed using the Discreet Fourier Transform (DFT). As a result the sequences of phaseograms and amplitude images were then obtained.

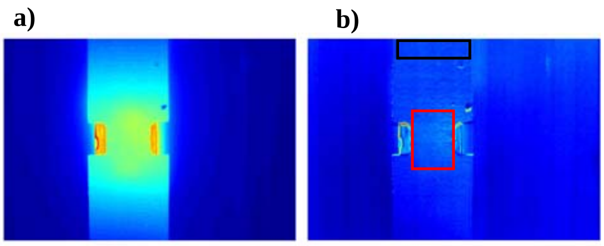

Fig. 4. Exemplary raw thermogram (a) and thermogram after normalization (b) with depicted sound region (black rectangle) and region of interest (red rectangle).

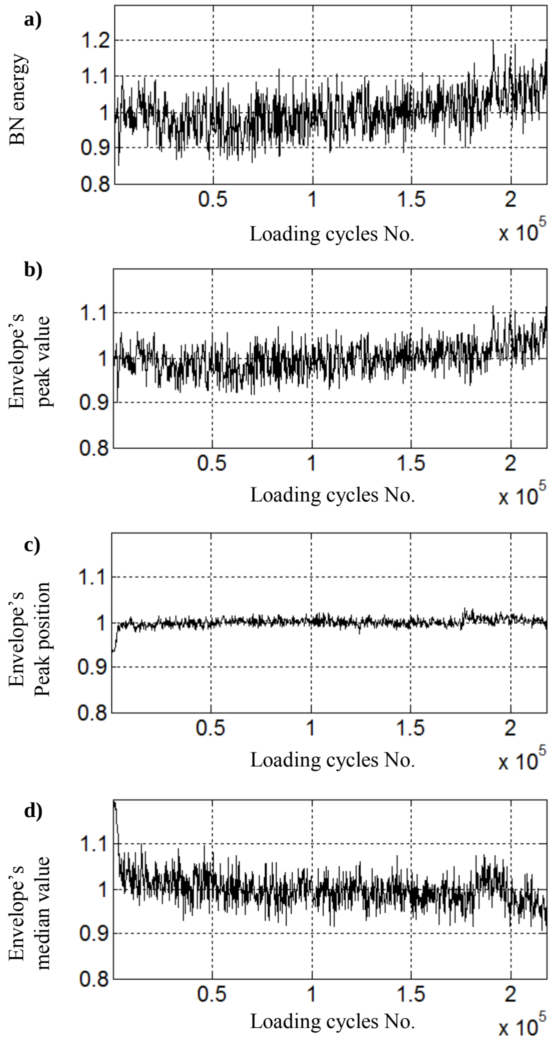

Fig. 5. Selected results obtained using Barkhausen noise method: a) BN signal's energy, b) envelope's peak value, c) envelope peak position, d) envelope's median value; all distributions were normalized by the mean value of the parameters.

Experimental results and discussion

Generally the fatigue process can be divided into three stages: a microstructural change ending with a fatigue breakthrough stage, a development of crack growth area in the material, and finally a destruction of the material [2].

Selected results of the experiments are presented in Fig. 5 – Fig. 9. In case of the BN, the distributions of signals energy, peak value, position and median value of BN burst envelope are shown (Fig. 5). At the beginning of the fatigue process (until $2.5 \cdot 10^3$ of fatigue cycles) one can notice significant change of parameters value with cycles which is especially visible on plots of peak position and median value. The detail views of this part are presented in Fig. 6. The observed behaviour can be explained by the process of microstructural changes resulting in material softening [6].

This stage is relatively short and material properties stabilize after 10^3 of loading cycles. The second stage, in which the micro-cracks growth occurs, lasts most of the time of whole fatigue process. During this part Barkhausen noise parameters do not change significantly, however there can be seen week trends in achieved distributions (Fig. 5 a, c and d). Final stage (begins around to $2 \cdot 10^5$ of fatigue cycles) corresponds to rapid growth of the crack area and final fracture of the material. This can be also noticed by significant change of trends on the obtained parameters distributions (Fig. 5 a, b and d).

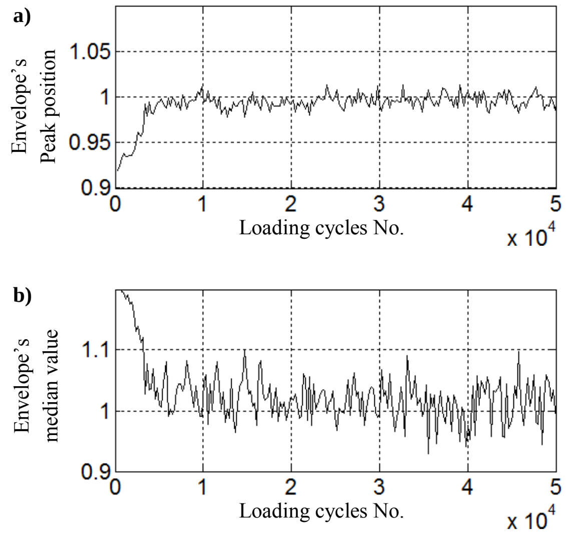

Fig. 6. Plots of BN envelope peak position (a) and median value achieved at the beginning of the fatigue process; all distributions were normalized by the mean value of the parameters.

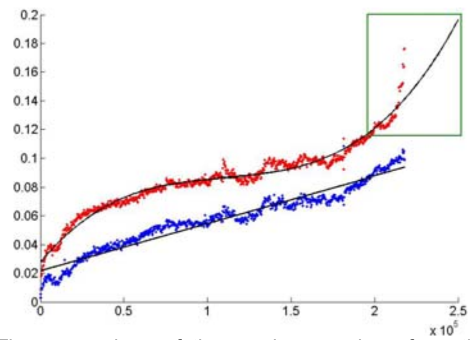

Fig. 7. The comparison of the maximum values from the sound region (blue line) and region of interest (red line). The rectangle marks the crack generation indication.

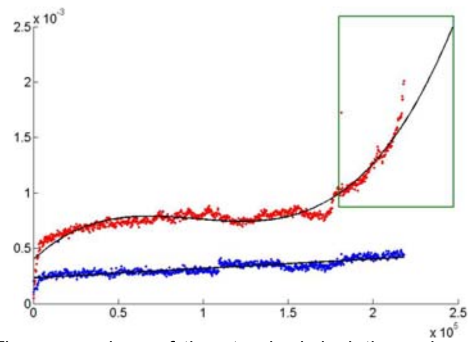

Fig. 8. The comparison of the standard deviation values from the sound region (blue line) and region of interest (red line). The rectangle marks the crack generation indication.

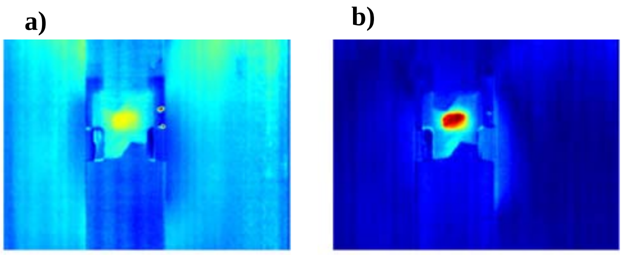

Fig. 9. The phase a) and amplitude b) images of the sample with crack generated in the load process

In case of the IRT the comparison between the maximum and standard deviation regions from the selected regions are shown in Fig. 7 and Fig. 8. The red lines show the parameters' values in the region of interest. Both parameters are significantly different from the sound area. Considering the BN results, also in case of IRT it is possible to distinguish three characteristic stages of the parameters behaviour. In the initial phase of the fatigue process one can notice the growth of the parameters’ values which then weakens and stabilize. Finally one can easily see the significant increment of both parameters while the rapid crack growth and fracture takes place (marked with green rectangle in Fig. 7 and Fig. 8.).The crack visualization using the IRT was also possible. The Fig. 9 shows the amplitude and phase images chosen from the thermograms' sequence processed using the DFT. The heat transfer within the defected area is significantly disturbed, thus the crack is visible as the border between heated and unheated area. The hot spot visible in both images is produced partially by the BN transducer.

Conclusions

This paper presents the experimental methodologies and the results of the electromagnetic and infrared investigation of the steel samples under fatigue cyclic loading. The selected methods allow to observe the fatigue process by means of different physical aspects (e.g. the changes of magnetic and thermal properties during fatigue). Thereby making it possible to obtain the wider range of information about the state of the structure. The obtained results confirmed the possibility of using both methods to acquire information and then proceed the assessment of the degradation stage. However the interpretation of various aspects of the fatigue process is complicated. Therefore further work must be carried out on monitoring the fatigue process for steel representing different initial mechanical characteristics. Additionally the integration of multisource data will be carried out too.

***Authors**: Grzegorz Psuj, West Pomeranian University of Technology, Szczecin, al. Piastów 17, 70-310 Szczecin, Poland, gpsuj@zut.edu.pl , Barbara Szymanik,* West Pomeranian University of Technology, Szczecin*, al. Piastów 17, 70-310 Szczecin, szymanik@zut.edu.pl*

REFERENCES

[1] Dobmann G., Ciclov D. C., Kurz J. H., NDT and fracture mechanics. How can we improve failure assessment by NDT? Where we are – where we go?, Insight, Vol. 53, No. 12, 2011
[2] Palit Sagar S., et al., “Magnetic Barkhausen emission to evaluate fatigue damage in low carbon structural steel”, International Journal of Fatigue, vol. 27, 2005, pp. 317-322
[3] Psuj G., Chady T., Enokizono M., Observation of material degradation under fatigue and static loading condition using selected electromagnetic NDT methods, *Material Science Forum*, 721, 120, 2012, 120-126
[4] Maladegue X., Theory and practice of infrared technology for nondestructive testing. JohnWiley and Sons, 2001.
[5] Chady T., Psuj G., Fuzja elektromagnetycznych metod testowania w zastosowaniu do wizualizacji zmian materiałowych w stalowych elementach poddawanych naprężeniom, Przegląd Elektrotechniczny (Electrical Rev.) R.82, Nr 1/2006, pp.1-7
[6] Lindgren, Lepisto T., “Effect of cyclic deformation on Barkhausne noise in mild steel”, NDT and E International, 36 (2003), pp. 401-409.