EXAMINATION OF SERVICE LIFE OF POWER SYSTEM COMPONENTS MADE OF P91 STEEL (X10CrMoVNb9-1) USING IMPEDANCE SPECTROSCOPY AND MAGNETIC RESONANCE TECHNIQUE

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Abstract. The martensitic steel P91 belongs to the group of steels used in power plants. Machine components and equipment constructed with steels from the group (15HM -13CrMo44 (DIN) and 13HMF) are utilized in service at increased temperatures. Such steels are exposed to thermal fatigue loads, accelerated corrosion, dynamic creep and relaxation (ratcheting) due to tension fatigue. The harsh operation conditions (temperature, pressure) have diverse influence on the evolution process of their physical parameters. In case of most steels used in power plants the magneto-inductive measurement of properties is a convenient technique for testing samples when continuously applied. The paper presents results of tests performed on P91, 15 HM and 13 HMF steel samples. A low cost service life monitoring is proposed.

1. Introduction

Among the most precise methods characterizing degradation processes we may find neutron and X-ray procedures [1]. The magneto-inductive methods sensitive to the changes in electrical and magnetic parameters come next. The magneto-inductive methods were used for crack detection. Nowadays these methods are being introduced too to the detection of operational fatigue processes [3, 6, 7, 8]. Detailed comparison of initial (input) material parameters with parameters of the material used for duration of tens of years is, in many cases, directly impossible. However, such a comparison, is indispensable, for NDT and NDE. The presented photographs show in turn: the fragments of inlet chambers of the second-stage superheater of the re-superheated steam (M-2) (Fig. 1a), the inlet chamber of the live steam from the third stage (Fig.1b) superheater of the live steam, and the knee of the re-superheated steam pipeline (Fig. 1c).

Fig. 1. Fragments of power industry installations, locations where samples were obtained are shown; from the left: inlet chamber 15HM, inlet chamber 20H12M1F, knees 13HMF

The operational evolution of mechanical [2] and magnetic parameters is non-linear, directly correlated with chemical composition of the material and the macroscopic structural and operational load characteristics. One method of determining the operational variability of magnetic properties will be described here for several types of steel. The impact of type of the operational loads on the magnetic and electrical parameters of the material is diverse on account of material's chemical composition and original micro structure. For each type of steel, an independent, individual testing is therefore required.

2. Steel's characteristics

Chrome-molybdenum 15HM (PN-75/H-84024, 13CrMo4 5 acc. EN) steel is stainless type of steel, dedicated to work at higher temperatures. 15HM steel is steel with good ductility at both high and low temperatures. This steel is well suited to treatment, used in chemistry and power engineering devices, operating at temperatures elevated to 500°C. This steel is used for superheater tubes and wires, pressure tanks and sheet metal drums.

Steel grade	Standard	Chemical composition									
		C	Mn	Si	P	S	Cu	Cr	Ni	Mo	other
15HM	PN	0.11 0.18	0.40 0.70	0.15 0.35	max 0.040	max 0.040	max 0.25	0.70 1.00	max 0.35	0.40 0.55	Al max 0.02

Constructional alloy steel - chromium-molybdenum-vanadium 13HMF PN-75/H-84024 (or its equivalent 14MoV6 3, 1.7715) was used in the production of boiler tubes, parts of steam turbines and boilers working at temperatures up to 560°C.

Steel grade	Standard	Chemical composition									
		C	Mn	Si	P	S	Cu	Cr	Ni	Mo	other
13HMF	PN	0.10 0.18	0.40 0.70	0.15 0.35	max 0.040	max 0.040	max 0.25	0.30 0.60	max 0.30	0.50 0.65	Al max 0.02

Steel 20H12M1F (X20CrMoV12 1 acc. DIN) was used for pipes in power equipment operating at temperatures up to 600°C. This grade or its equivalent is provided for round-rolled bars, forgings, round bars, flat bars.

Steel grade	Standard	Chemical composition									
		C	Mn	Si	P	S	Cu	Cr	Ni	Mo	other
20H12M1F	PN	0.17 0.23	0.30 0.80	0.10 0.50	max 0.035	max 0.035	-	0.70 1.00	11.00 12.00	0.30 0.80	V 0.25 0.035

The types of steels listed above constituted the basis of post-war power industry, based mostly on GOST standards. Steel P91 (XCrMoVNb9 1 acc. DIN) is especially suited to steam boiler, boiler parts, boiler drum, pressure vessel construction. It may operate continuously at temperatures up to about 650^{o}C.

Steel grade	Standard	Chemical composition										
		C	Mn	Si	P	S	Cr	Ni	Mo	V	Nb	other
P91 XCrMoVNb9 1 W-1.4903	ASME DIN	0.08 0.12	0.30 0.60	0.20 0.50	max 0.035	max 0.035	8.0 9.5	<0.40	0.85 1.05	0.18 0.25	0.06 0.1	N: 0.03 0.07

P91 steel and its predecessor, 20H12M1F steel, belong to the group of martensitic steels.

3. Tested material

As result of the conducted measurements, “virginal” materials, found in the storehouses on the market, were compared with material utilized in power plant systems currently used, made of steels 13HMF, 15HM and 20HM12M1F.

Metallographic tests were conducted using Hitachi S-4200 scanning electron microscope coupled with an EDS system used for X-ray microanalysis. Visual observations performed at magnitudes of 200x, 500x, 1000x and 2000x were conducted along the entire polished section of each sample. The characteristic micro structure elements detected in each sample were digitally recorded. The selected micro structures are presented in Figs 2 and 3.

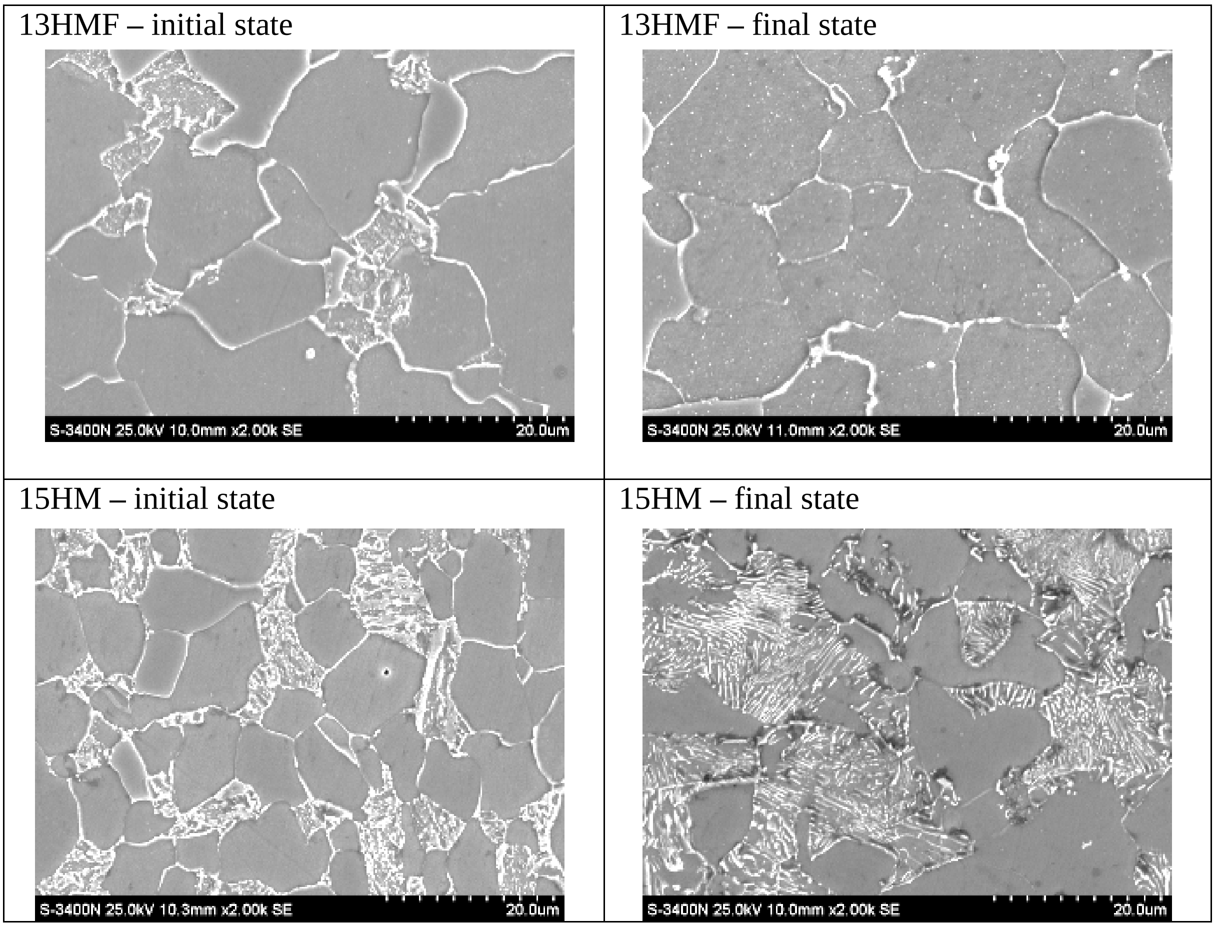
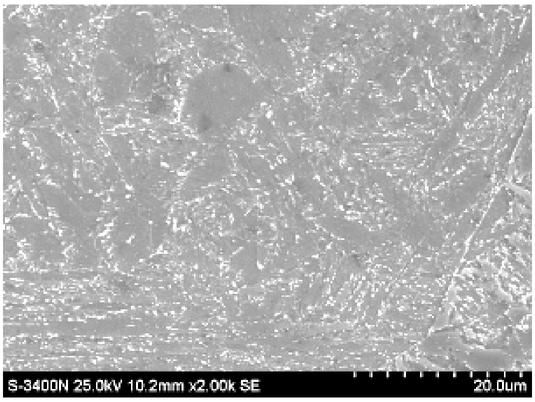
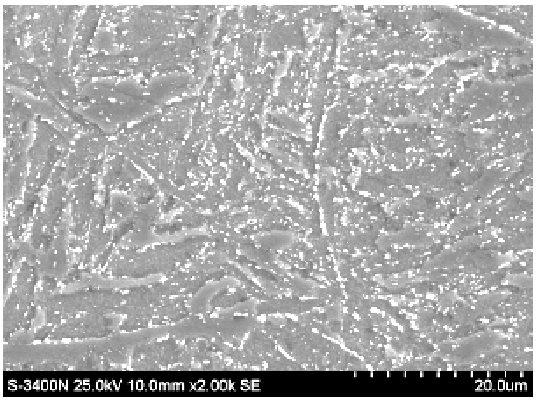
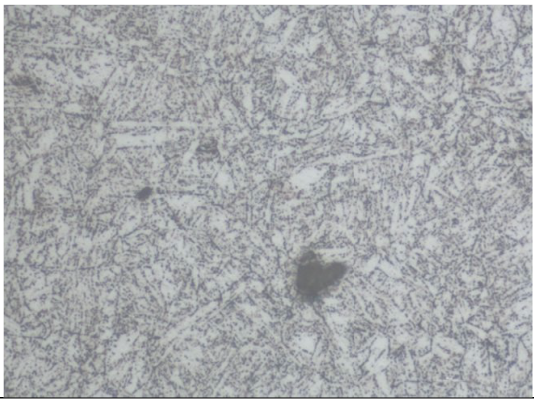
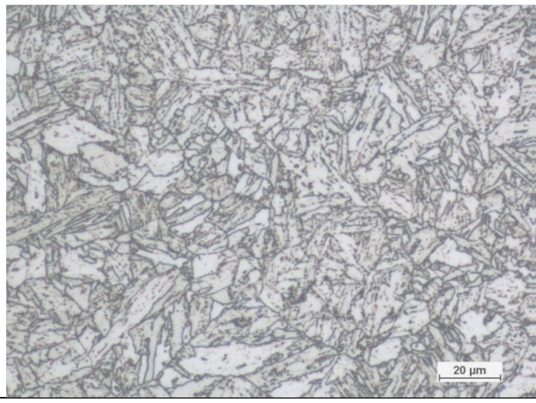


Fig. 2. Comparison of changes in steel micro structures for 13HMF and 15HM steels

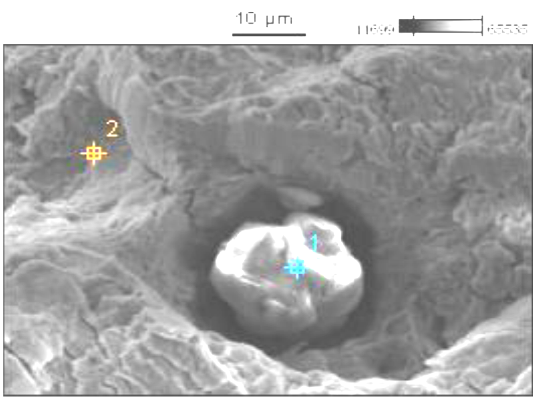
20H12M1F – initial state	20H12M1F – final state
	
P91 – initial state	P91 – final state
	

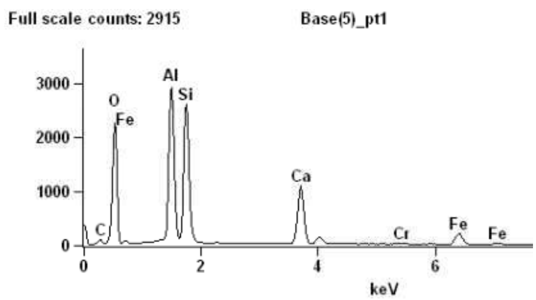
Visual representation of operational changes in steel micro structure:

13HMF initial state – ferrite + pearlite 15HM initial state – ferrite + pearlite 20H12M1F initial state – martensite	13HMF final state – bainite 15HM final state – ferrite + pearlite 20H12M1F final state martensite + carbides

Fig. 3. Comparison of changes in steel micro structures for 20H12M1F and P91 steels

When P91 steel structures are observed, operated previously or artificially aged, typical micro structure is tempered martensite with precipitated carbides bordering on original austenite and martensite strips, and their visible growth [2]. During lab tests which utilize fatigue-testing machines, the most prominent kind of degradation consists in cracking of non-metallic inclusions; the cracks are propagating to the inclusion pocket walls and neighbouring structures – see Fig. 4.





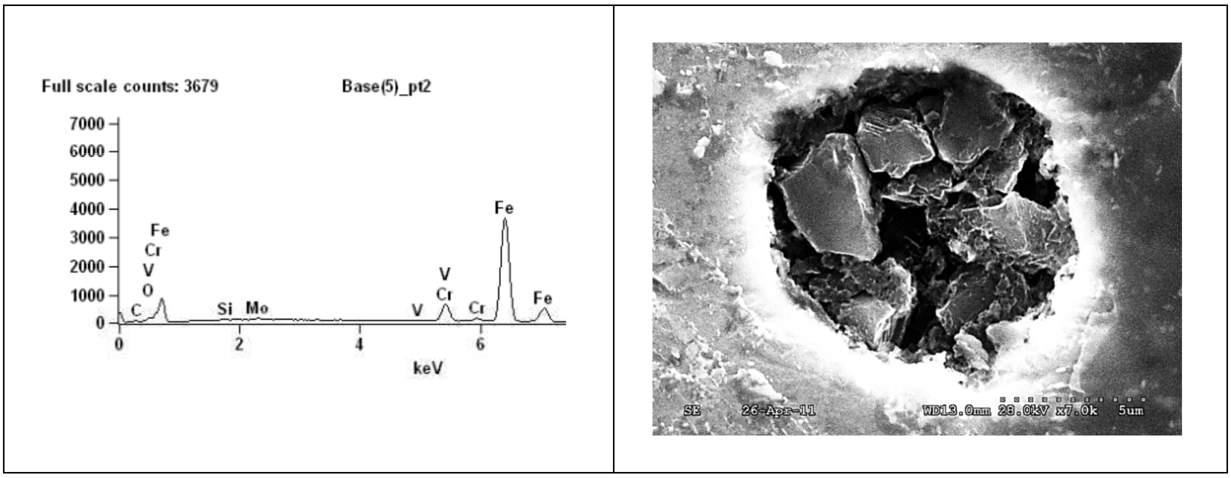


Fig. 4. Images and composition of non-metallic inclusions of the input material, before and after mechanical loading at the MTS servo hydraulic machine

4. Measurement theory

The material's parametric relationships may be represented in the simplest way using an appropriate model. The tested material (characterized by its magnetic and electrical parameters [4,10,11]) affects the measurement of the electrical parameters of a search coil due to inductive coupling *M* (Fig. 5).

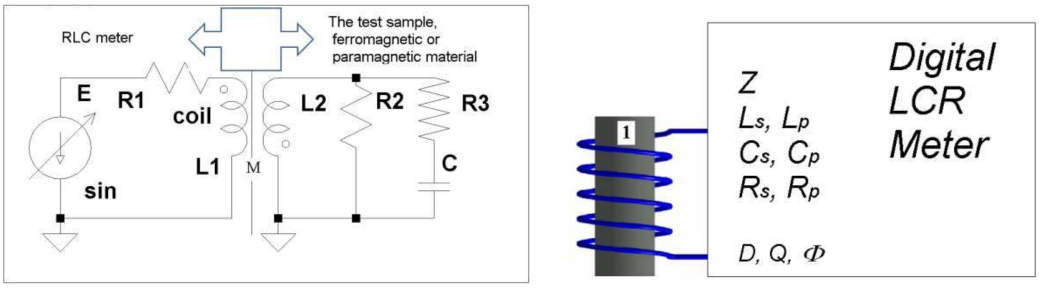


Fig. 5. Model of the measurement circuit [1]

One of the simplest models described by Forster was selected [4]. When ratios of the normalized impedance components [4] were compared

$$\frac{\omega L_p}{\omega L_0} \quad \text{and} \quad \frac{R_p - R_0}{\omega L_0}, \tag{1}$$

information was obtained on the generalized impact of the operational processes on micro structure changes and defects. By measuring the components L_s and R_s (elements connected in series, or in parallel) of the tested impedance circuit, information on the tendency of changes in the permeability and electrical conductance is acquired.

When results obtained from material samples are compared, it is important to maintain sample geometry (sample radius r_0) and measurement coil geometry on account of the significant impact of η coefficient, where $\eta = (D_p / D_s)^2$. This is shown in the theoretical formulas calculated with the help of Mathematica software from the following equations:

$$\frac{\omega L}{\omega L_0}[\gamma\_, \mu_{re}\_, \omega\_\eta] = 1 - \eta + \eta\mu_{re}\mathrm{Re}[\mu_{ef}], \tag{2}$$

$$\frac{R - R_0}{\omega L_0}[\gamma\_, \mu_{re}\_, \omega\_, \eta] = -\eta\mu_{re}\mathrm{Im}[\mu_{ef}], \tag{3}$$

$$\eta = (\frac{D_p}{D_s})^2; \; k = Sqrt[-i \times \omega \times \gamma \times \mu_r \times \mu_o], \tag{4}$$

$$\mu sk = \frac{2}{k \times ro} \times \frac{J_1(k \times ro)}{J_0(k \times ro)}, \tag{5}$$

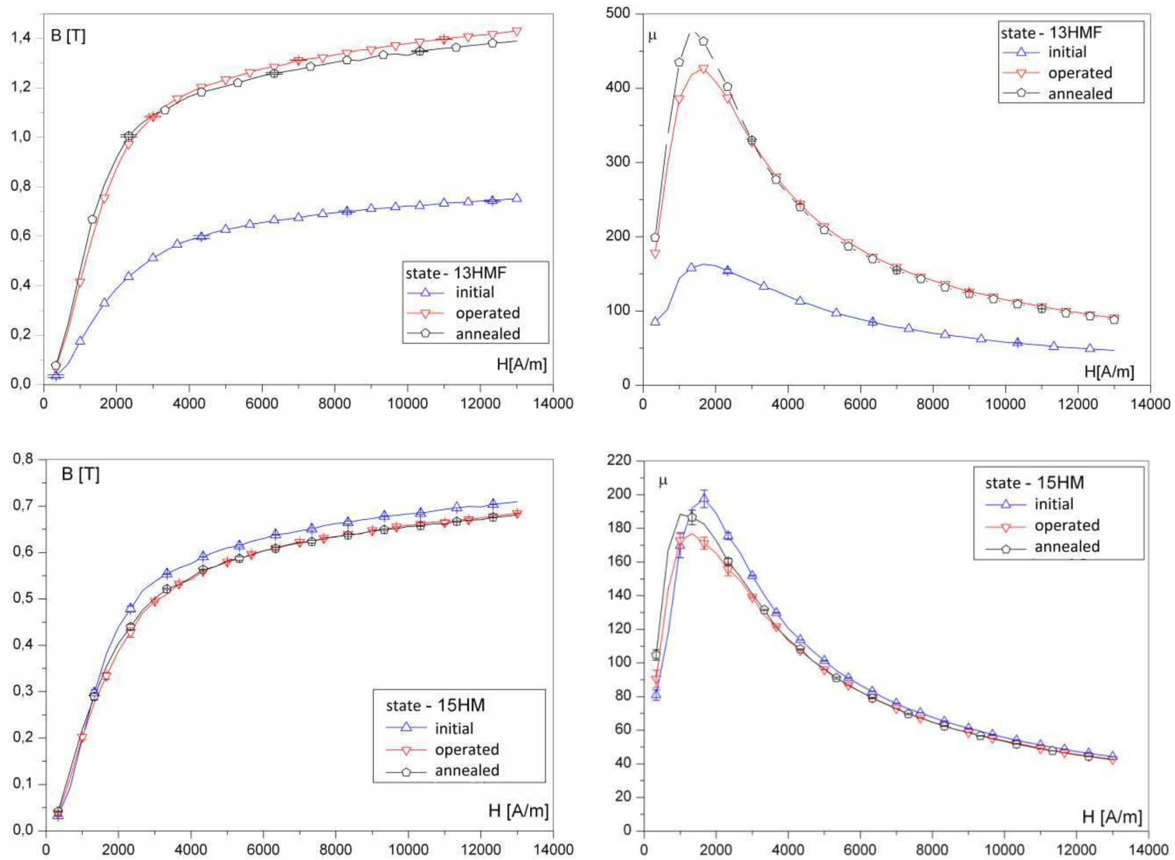
The limit frequency is defined by the relationship:

$$f_g = 2 / (\pi \times D_p^{\,2} \times \gamma \times \mu_o \times \mu_r) \tag{6}$$

It characterizes the penetration of eddy currents and magnetic field into a cylindrical sample.

5. Measurements of magnetic parameters

The significant changes in inductance of the measurement coil tested with sample taken out of service were observed for steels 13HMF and 20H12M1F. In 15HM steel the changes were detected only for the maximum dynamic permeability. The curves of initial magnetization and dynamic magnetic permeability for initial and worn material and for material annealed in order to eliminate second-order stresses [12-15] are shown in Fig. 6.



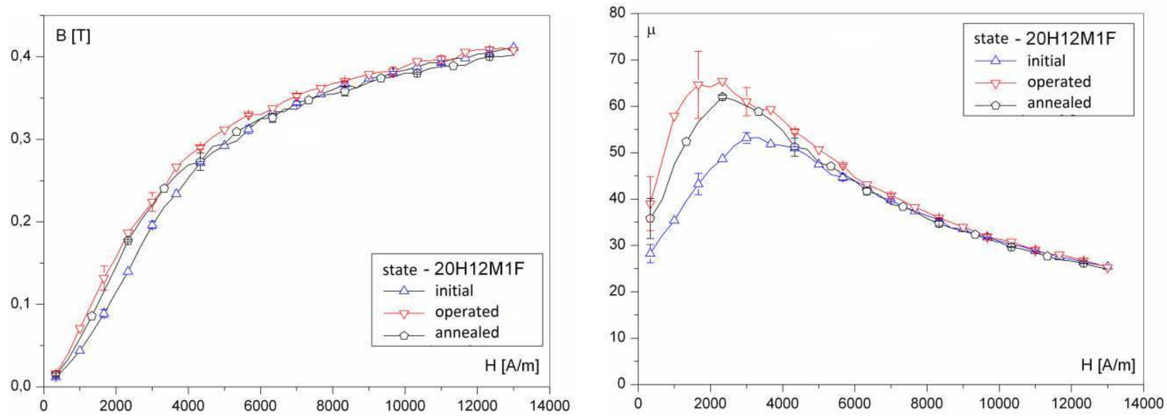


Fig. 6. Comparison of changes in steels' operational parameters

Each steel type shows operational changes in its parameters. For field intensities up to 200A/m, the values of the standard deviations confirm the feasibility of using magnetic measurements as observer of material's fatigue condition.

6. RLC bridge measurements of P91 steel electrical and magnetic parameters' evolution

20H12M1F steel have been the basis for experiments and tests [14,15]. In case of P91 steel, material worn out during industrial operation was not available. Therefore the tests were run with unused (brand-new) samples of P91 steel and with annealed samples. The materials in their initial state and after annealing at 600°C were compared. The chart presenting measurement results in five basic frequency ranges of the RLC bridge (100Hz, 120Hz, 1kHz, 10kHz, 100kHz) [11] is shown in Fig. 7.

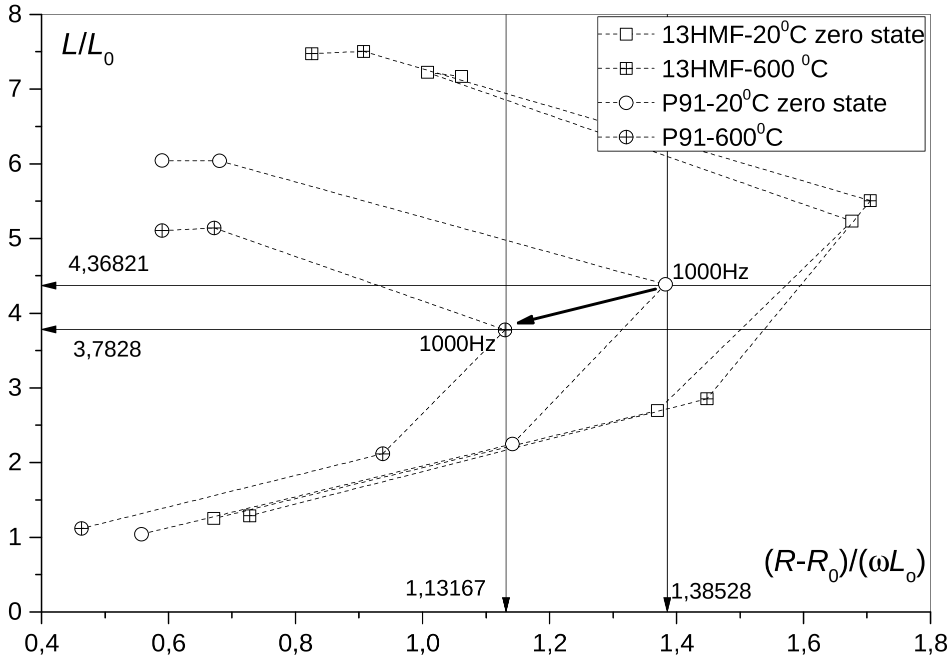


Fig 7. Comparison of changes in normalized impedance components, for two types of steel used in power engineering

Comparable changes of material, in relation to operational cycles, are obtained when annealing for 80 to 100 thousand hours at a temperature equal to 600°C. The real changes of effective magnetic permeability and electrical conductance can be derived numerically from relative changes of the normalized impedance components shown in Fig.7. The significant changes of P91 steel parameters are accompanied by substantial changes in mechanical parameters [2].

7. Design solutions

Changes in electrical parameters also include change of resonant frequency of the measurement circuit [5, 9, 10, 11]. The presence of ferromagnetic body close to the wires is the reason why such circuits become non-linear (Fig.8). The wire reaction to the ferromagnetic material places the above issue within the inspection tasks of non-destructive diagnostic methods NDT/NDE [5, 10, 16-18]. Parameters of pipeline section may be controlled via induction coupling of one-wire measurement cable even at operational temperature. If the wire probe is equipped with silicon coating, the high pipeline temperature is less degrading the sensor properties than in case of sophisticated extensometers.

Fig. 8. Example of using LDC converter in the pipeline inspection

In the lab, the testing of stretching of a metallic glass strip was started, using a two-channel LDC1612 transducer. The photo of the test stand and the records of the measurement results of the tension in the foil are shown in Fig.9.

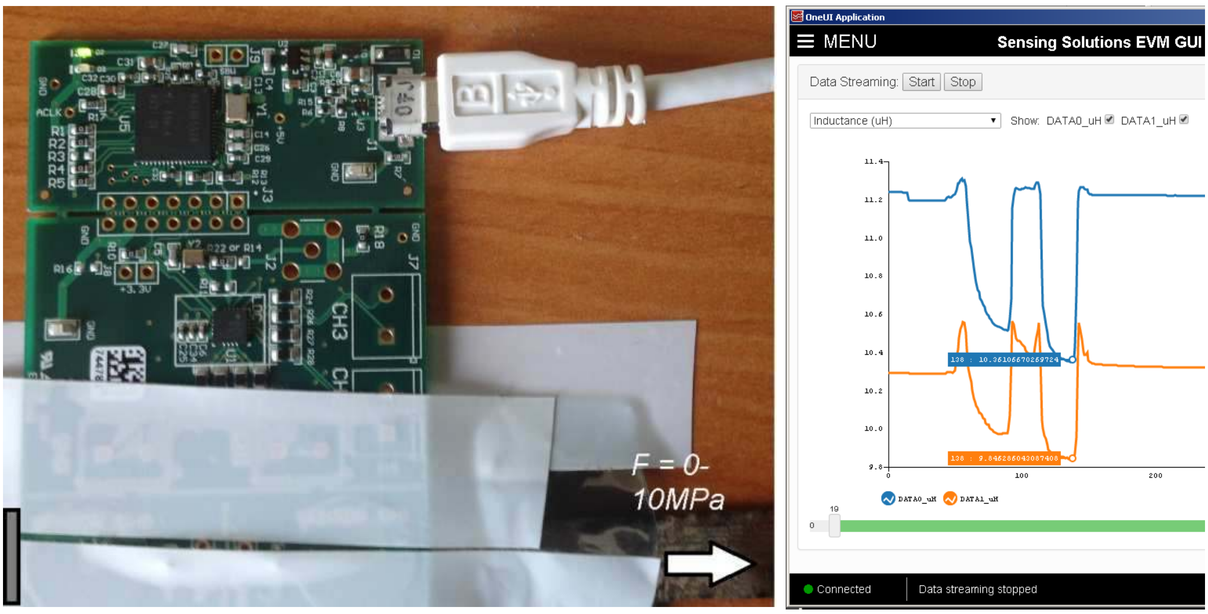


Fig. 9. Recording of stress changes in the metallic glass foil

This transducer records also changes in the resonance coupling frequency.

8. Conclusion and future work

Impedance spectroscopy, normalized impedance components and magnetic resonance are prospective observers of the material's degradation state. The successive advantage presented by these methods is the possibility of decreasing the costs of the equipment, without losing repeatability and sensitivity for detection. The simple diagnostic methods do not have to pose any hazard to the companies manufacturing flaw detection devices, but they may be used for modification of standard procedures in crack detection. The proposed method excited some interest in several academic centres at home; first industrial applications have been executed. The measurement modules [16, 17, 18] of the company TI, accessible in the market, seem like a good step towards further miniaturization and cost reduction, while the metrological quality standard is maintained.

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