Budapest University of Technology and Economics

Micro-Magnetic Examination of Thermal Fatigued Heat-Resistant Steels.

-Influence of thermal fatigue on the magnetic properties of two power plant steels-

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-PhD dissertation-

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NYILATKOZAT

Alulírott Kwak Dong Ho kijelentem, hogy ezt a doktori értekezést magam készítettem, és abban csak a megadott forrásokat használtam fel. Minden olyan részt, amelyet szó

ABSTRACT

In the present research work, it was studied whether magnetic approaches can be used for the life prediction evaluation and defect measurement in heat-resistance E911 ferritic heat resistant steel and in 15128 ferritic-bainitic steel. Destructive and non-destructive test methods were used. Surface hardness test, transmission electronmicroscopical investigations, coercivity measurements and Barkhausen noise measurements were also used. This research is to clarify the dependency how the thermal fatigue process influences the magnetic properties of the two different steel types, which are often used in power plant applications. It will be also tested, whether the Barkhausen noise measurement can be applied to follow the microstructural changes caused by thermal fatigue in case of the tested steel types.

Keywords : thermal fatigue, Barkhausen noise, heat-resistant steel, non-destructive test.

ABSTRACT

Jelen PhD dolgozat célja megállapitani, hogy a különböző mágneses mérési módszerek alkalmazhatóak-e t a E911 jelű ferrites- és 15128 jelű ferrit-bénites melegszilárd acélok maradék élettartamának meghatározására illetve a károsodás mértékének mérésére. Különböző roncsolásos és roncsolásmentes vizsgálati eljárások kerültek alkalmazásra. Felületi keménység mérése, transzmissziós elektronmikroszkópos vizsgálat, koercitív erő mérése ill. Barkhausen-zaj mérési eljárásokat használtam a kutatás során. A dolgozat igazolja a termikus fáradási *folyamat és a mágneses tulajdonságok közötti egyértelmű kapcsolatot a vizsgált melegszilárd acélok esetén, amelyek erőművekben gyakran kerülnek alkalmazásra. Továbbá vizsgálatokat végeztem, hogy a Barkhausen-zaj mérési eljárás alkalmas-e az említett acélok termikus fáradása során bekövetkező mikroszerkezeti változások követésére.*

Kulcsszavak: termikus fáradás, Barkhausen-zaj, melegszilárd acél, roncsolásmentes anyagvizsgálat.

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I. INTODUCTION

1.1. Research summary

In contemporary human life, electric energy becomes an indispensable energy form and most of the electric energy production depends on different power systems making the conversion from thermal energy to mechanical energy. Consequently, the efforts of the numerous research and development projects have been concentrating on thermal efficiency and reliability problems in the different structural elements of power plants. The reliability of the materials which are used in steam turbines and boilers, especially at high temperature and high pressure, is directly connected to the continuous and stable generation of electricity. This is the reason why this research area is regarded nowadays as one of the most important research fields of power plant materials.

During the present research work, it was studied whether magnetic approaches can be used for the life prediction evaluation and defect measurement in heat-resistance E911 ferritic heat resistant steel and in 15128 ferritic-bainitic steel.

The tested material types are usually operating under creep conditions and suffering from thermal fatigue, which is caused by rapid (local) temperature changes. During the research work, we used destructive and non-destructive test methods. Through the destructive method, we were able to follow the structural changes caused by the applied thermal fatigue process, using microscopical and electronmicroscopical investigations.

Surface hardness test, transmission electronmicroscopical investigations, coercivity measurements and Barkhausen noise measurements were also used.

The E911 ferritic heat resistant steel is weldable and it has a low price advantage compared with austenitic steel types. In addition, we were able to apply magnetic tests in this ferritic steel because ferritic heat resistant steels are usually in a ferromagnetic state.

1.2. Purpose of research

It is well known that the demand for electric energy, which is necessary to industry and human life, is not always constant, but changes depending on the time of day and of the season. To keep up with the demands, the power plants are adapting to this. For example in many power plants, the materials used as boiler or turbine materials, are not always operating in the temperature range 500℃~550℃ but have a temperature fluctuation between 20℃ and the operating temperature, for example 550℃. During the heating and cooling process, thermal stresses may arise in the structural elements. These stresses may cause crack initiation and later crack spreading in the important structural elements of power plants due to thermal ageing, which is one of the key embrittlement mechanisms of pressure vessel materials.

The non-destructive methods can be useful for the detection of fracture caused by fatigue process. A crack, which can be detected visually from the surface, is very restricted, and the stability of the equipment has already damaged seriously if the crack is in progress until it can be detected visually. Consequently, if it is possible to follow the changes of the microstructure of material before the crack occurs, this could be very useful for managing the reliable operation of the structural element. In addition, the E911 ferritic steel and 15128 type steel, which are tested in this research, are actually used in many European power plants.

In this research, one NDT method is applied, which is sensitive to the inside structural changes. The use of a proper NDT testing – as the measurement of magnetic properties like the Barkhausen noise - gives reliable understanding of material behaviour. [1]

The main goal of this research is to clarify the dependency how the thermal fatigue process influences the magnetic properties of the two different steel types, which are often used in power plant applications.

It will be also tested, whether the Barkhausen noise measurement can be applied to follow the microstructural changes caused by thermal fatigue in case of the tested steel types.

II. THEORETICAL BACKGROUND

2.1. Fatigue failure and thermal fatigue

2.1.1. Fatigue failure

The definition of fatigue is the effect on metal of repeated cycles of stress. The insidious feature of fatigue failure is that there is no obvious warning, a crack forms without appreciable deformation of structure making it difficult to detect the presence of growing cracks. Fractures usually start from a small notch or scratches, which are caused by a localised concentration of stress. Failure can be influenced by a number of factors including size, shape and design of the component, condition of the surface or operating environment. [2]

Fatigue fracture processes usually occur in four steps. [3]

- First step - Crack initiation- initiation stage of fatigue damage.
- Second step - Slip band crack growth- The initial crack growth propagates into the direction on the plane having a big shearing stress. This is called Stage I Crack Growth.
- Third step - Crack growth on planes of high tensile stress - The crack grows with the vertical direction of the maximum tensile stress. This is called Stage II Crack Growth.
- Fourth step - Ultimate ductile failure – After the crack grew enough, the load becomes intensive in the remainder cross section and it becomes destructive.

Depending on the factor of fatigue test and quality of the material, the holding ratio of the each fatigue steps has been changed. In case of low cycle fatigue, in this research, the second step has relatively main role during the fatigue process. [4]

Fatigue fracture or fatigue quality of the material is expressed by the S-N curve involving stress and the number of fatigue cycles. Generally, the number of loaded fatigue cycles is more than 10^5. If the number of cycles is less than 10^5, it is called low cycle fatigue. The explaining method of fatigue fracture is different following the number of fatigue cycle because the fatigue characteristics are caused by different strain value in each case. In some cases of the low cycle fatigue, the main factor that effects to fatigue can be the thermal factor. [5]

The expression regarding strains in fatigue fracture is composed of to parts.

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} \tag{2.1}$$

The total strain range $\Delta\varepsilon$ is composed of the elastic strain range $\Delta\varepsilon_e$ and plastic strain range $\Delta\varepsilon_p$.

Regarding the plastic strain range, it is called Coffin-Manson relation. The expression is shown at (2.2).

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f (2N)^c \tag{2.2}$$

ε_f= fatigue ductility coefficient,

N=number of fatigue failure cycle,

c=fatigue ductility index

The case of elastic strain part is shown in equation (2.3). This relation is explained by Basquin equation.

$$\frac{\Delta\varepsilon_e}{2} = \frac{1}{E}\sigma_f (2N)^b \tag{2.3}$$

E=modulus of elasticity

σ_f=fatigue strength

b=fatigue strength index

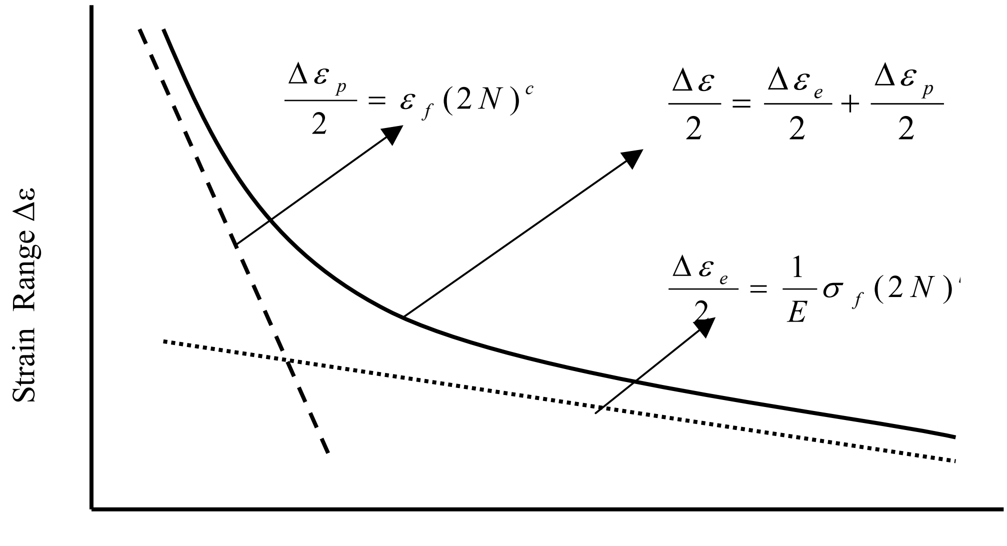


Figure 2.1. Fatigue strain and life time curve

A general S-N curve can be analyzed by two equations in figure 2.1. The plastic strain equation is explained in the low cycle zone and the elastic strain equation is regarded to high cycle fatigue. It is known that very often the most important factors in the low cycle fatigue process are the thermal effects.

2.1.2. Thermal fatigue

The state of power plant steels is far from being in equilibrium and this results in the changing of the structure of these materials during service especially at elevated temperatures. In power plant applications creep and low-cycle thermal fatigue are the most important life determining processes of the structural parts [6]

In the case of material fatigue fracture, a mechanical stress takes a main role of the fatigue stress source. However, it is not necessary only mechanical stress to be used. The thermal expansion by the changing temperature in the material will be able to operate with the stress role also. The equation of linear thermal expansion is expressed in the equation (2.4).

$$\sigma = \alpha E \Delta T \qquad (2.4)$$

α=coefficient of thermal expansion,

E= modulus of elasticity,

ΔT=variation of temperature

From (2.3) if the change of temperature (ΔT) has a large value, the change of the stress becomes high as well. If the destruction happens by thermal expansion occurring once, it is called thermal shock. If the destruction occurs by repeated small thermal stress, it is called thermal fatigue.

Especially stainless steels are very sensitive to thermal fatigue because they have relatively high coefficient of thermal expansion and low thermal conductivity.

Metallurgical explanation about the thermal fatigue process will be discussed. In many cases, the constantly changing material structure has predominating influence affecting the thermal fatigue behaviour and it is helpful to mention some of the important mechanisms involved. [5, 7]

The first one is ageing. One of most important events which happens during the thermal fatigue process is ageing. High temperature alloys in their operational conditions are not in metallurgical equilibrium. It is because of their metastable conditions that many alloys gain good high temperature properties. If the material is operating at a high temperature, the tendency is toward rearrangement of the microstructure in the general direction toward equilibrium. Thus, constituents that are in solid solution frequently tend to precipitate and may significantly change the properties of the material. For example, they precipitate in the grain boundaries, and can reduce the ductility of the material, particularly in creep loading. This precipitation may occur with or without the application of stresses, but generally stresses tend to hasten the action.

The second mechanism is corrosion. Other processes that may reduce the resistance against thermal fatigue are for example oxidation and corrosion. The surface of the material is usually in contact with oxygen or other gases capable of a chemical reaction with the materials at high temperature, where oxides may form as a result. Discontinuities formed at the surface layer either by cracking of the surface or by the disintegration of corroded product act as a source of stress concentration, which induces and propagates future cracks within the body of the material.

The third mechanism is hot and cold forming. Thermal fatigue tests also embody hot and cold forming of the material because of alternate thermal straining. This working is known to have important effects on the strength of the material and its subsequent properties.

The last is grain growth. One effect of forming is to cause the material to be susceptible to recrystallization. When grains are broken up, energy is stored in the slip planes and in the grain boundaries. Upon subsequent heating, there is a tendency for the material to recrystallize in order to achieve a state of lower accumulated energy. In many cases, the effect is to cause grain growth. Although there is no clearly defined relation between grain size and resistance to thermal fatigue, materials with large grain size generally have low ductility, which tends to indicate a poorer fatigue characteristic.

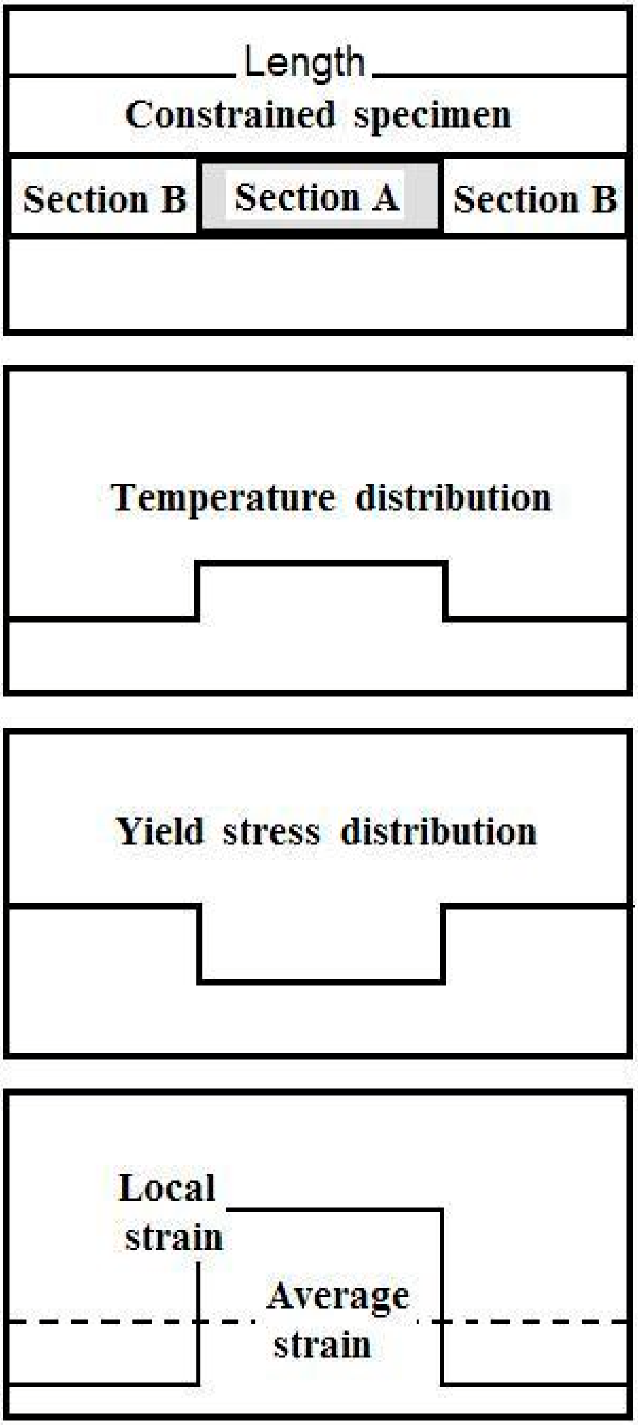


Figure 2.2. Inducing local strain by yield stress in high temperature region

2.1.3. Strain localization

Thermal fatigues of constrained specimens are frequently conducted on specimens having considerable no uniformities of temperature. Extremely large errors can result if the analysis does not account for the strain localization in such a case, see figure 2.2. The A-section is in the middle of the specimen. The test section is at a somewhat higher temperature, and therefore lower yield stress, than the remainder of the specimen. The stress strain curve can be approximated. For clarity, the load free condition is assumed when the specimen is cold. If the specimen is heated to a sufficiently high temperature to involve plastic flow, the stress developed will be the yield stress of the hot portion of the specimen. The cooler B section of the specimen will only have elastic strain, which is small in comparison with the plastic strain if the temperatures are assumed high enough. The major portion of expansion of the entire specimen will be absorbed in the plastic flow of the hot A-section. This is indicated by the strain distribution in figure 2.2.

A limiting condition exists when the temperature of the cooler section is only slightly lower than that of the hot section but sufficiently low to increase the yield stress to a value which exists in the hot section. Under this condition, the strain in the hot section can be four times the strain that would be present if the specimen were uniformly heated or if only the A-section were clamped and prevented from expanding. In practice, strain hardening and elastic strains modify the figure. But they do not invalidate the general principle that strain tends to be concentrated in the hot sections and that these strains can be much larger than those can computed on the basis of complete constraint of only the hot portion. The subject of strain localization is important in explaining the difference between low cycle fatigue experiments conducted under varying temperature and those conducted at constant temperature. [8]

2.2. Ferromagnetism and Barkhausen noise

2.2.1. Ferromagnetism properties

Ferromagnetism is one of the magnetic properties. This material has spontaneous magnetic moment even in zero applied magnetic fields. In order to explain the origin of spontaneous magnetization, the exchange field or energy should be considered. The exchange field gives an approximate representation of the quantum mechanical exchange interaction of atom. Equation 2.5 is expression of Heisenberg model. [9]

$$E_{ex} = -2J\vec{S}_i \bullet \vec{S}_j \qquad (2.5)$$

$$E_{ex} = -2JS_iS_j \cos\theta \qquad (2.6)$$

E_{ex} = Exchange energy

J = Exchange integral

S_i, S_j = Electron spin moment of neighbouring atoms

θ = Angle between two spins

The electrostatic energy of the system will depend on the relative orientation of the spins. The ferromagnetic material has a positive value of exchange integral. To be in the lowest energy state, two spin moments should be in parallel because the value of cosθ is 1 in parallel. This is the reason why the magnetic moment of ferromagnetic atoms is spontaneously oriented to the same direction within magnetic domains.

Otherwise, under the Curie temperature the magnetic moments of a ferromagnet are essentially parallel. In a whole ferromagnetic material, the magnetic moment may be very much less than the saturation moment, and the application of an external magnetic field may be required to saturate the specimen. The behaviour observed in polycrystalline specimens is similar to that in single crystals. Ferromagnetic specimens are composed of small regions called domains, within which the local magnetization is saturated.

The domain structure is natural consequences of the various contributions to the energy for example exchange energy, anisotropy energy and magnetic energy of a ferromagnetic body. The domain system is a solution for finding an energy equilibrium state.

Anisotropy energy is an energy in a ferromagnetic crystal that directs the magnetization along certain crystallographic axes called directions of easy magnetization. This is called the magneto crystalline or anisotropy energy. It does not come about from the exchange interaction.

The exchange and anisotropy energies induce the magnetization in one direction. In this case, total magnetic energy of the material increases. Therefore, the magnetic energy is reduced by dividing the crystal into domains magnetized in different directions and the magnetic energy sum of the domains has minimum value.

The directions of magnetization of different domains need not be parallel. An arrangement of domains has approximately zero resultant magnetic moment. The increase in the gross magnetic moment of a ferromagnetic specimen in an applied magnetic field takes place by two independent processes. [10]

• In weak applied fields - The volume of domains favourably oriented with respect to the field increases at the expense of unfavourably oriented domains.

• In strong applied fields - The domain magnetization rotates toward the direction of the field.

The behaviour of domain structure in the magnetization process can be described by the hysteresis loop. The coercivity is usually defined as the reverse field that reduces the induction to zero, starting from saturation. This is the most sensitive property of ferromagnetic materials.

The coercivity decreases as the impurity content decreases and also as internal strains are removed by annealing. The high coercivity of materials composed of very small grains or fine powders is well understood. In a single domain particle it is not possible for magnetization reversal to take place by means of the process of' boundary displacement, which usually requires relatively weak fields. Instead the magnetization of the particle must rotate as a whole, a process that may require large fields depending on the anisotropy energy of' the material and the anisotropy of the shape of the particle.

The coercivity of fine iron particles is expected theoretically to be about 0.05 T on the basis of rotation opposed by the crystalline anisotropy energy, and this is of the order of the observed value. Higher coercivity has been reported for elongated iron particles, the rotation here being opposed by the shape anisotropy of the demagnetization energy.

2.2.2. Barkhausen noise

Barkhausen noise (BN) is generated in ferromagnetic materials by the discontinuous movement of domain walls. This movement can be induced by applying a time varying magnetic field across the sample. The noise can be detected in the form of acoustic noise or in the form of voltage pulses, which are induced in a coil placed near the surface of the material.[11]

Ferromagnetic materials consist of small magnetic regions called domains. Each domain is magnetized along a certain easy direction of magnetization. All of these tiny domains actually are fully magnetized. Their directions of magnetization are oriented at random, however, so they cancel one another out. Domains are separated from one another by boundaries known as domain walls. Alternate magnetic fields will cause domain walls to move back or forward. In order for a domain wall to move, the domain on one side of the wall has to increase in size while the domain on the opposite side of the wall shrinks. The result is a change in the overall magnetization of the sample. The movement of domain walls can be one of the keys to explain the stress analysis of steels.

If a coil of conducting wire is placed near the sample while the domain wall moves, the resulting change in magnetization will induce an electrical pulse in the coil. The first electrical observation of domain wall motion was reported in 1919. The magnetization process, which is characterized by the hysteresis curve, in fact is not continuous, but is made up of small, abrupt steps caused when the magnetic domains move under an applied magnetic field. When the electrical pulses produced by all domain movements are added together, a noise-like signal called Barkhausen noise or jump is generated. [12]

Barkhausen noise has a power spectrum starting from the magnetizing frequency and extending beyond 2 MHz in most materials. It is exponentially damped as a function of distance it has travelled inside the material. The extent of damping determines the depth from which information can be obtained. The main factors affecting this depth are frequency range of the Barkhausen noise signal, conductivity and permeability of the test material. Measurement depths for practical applications vary between 0.01 and 1.5 mm. [13]

Two important material characteristics will affect the intensity of the Barkhausen noise signal. One is the presence and distribution of elastic stresses that will influence the way domains choose and lock into their easy direction of magnetization. This phenomenon of elastic properties interacting with domain structure and magnetic properties of material is called a magneto elastic interaction. Because of magneto elastic interaction, in most steel materials with positive magnetic anisotropy, compressive stresses will decrease the intensity of Barkhausen noise while tensile stresses increase it. This fact can be exploited so that by measuring the intensity of Barkhausen noise the amount of residual stress can be determined. The measurement also defines the direction of principal stresses.

The other important material characteristic, which affects the Barkhausen noise, is the microstructure of the sample. This effect can be broadly described in terms of hardness. The noise intensity continuously decreases in microstructures characterized by increasing hardness. In this way, Barkhausen noise measurements provide information on the micro structural condition of the material.

Many commonly used surface treatments such as induction hardening involving some modification of both stress and microstructure can be readily detected using the method. Various dynamic processes such as creep and fatigue similarly induce changes in stress and microstructure can be monitored with Barkhausen noise.

Practical applications of the magneto-elastic Barkhausen noise method can be broadly divided into three categories. The first is evaluation of residual stresses. The provided micro structural variables can be reasonably controlled. Residual stresses are important in the design, fabrication, and service life of many structures and components. Some service-induced stresses are considered harmful predecessors of fatigue cracking. To detect and measure stresses such as these, the Barkhausen noise method makes use of the distinctive behaviour of magnetic domains, small regions of local magnetization oriented in various directions within a ferromagnetic material. The second application is the evaluation of micro-structural changes. The third one is testing of the surface defects, processes and surface treatments that may involve changes in both stresses and microstructure.

A measurement is made by applying a controlled, changing pattern of magnetization, and sensing the resulting electromagnetic effects in the form of voltage pulses induced in a small inductive coil probe. Amplified and electronically processed, this signal can be presented on an oscilloscope or as a meter reading.

Precise quantitative results can be achieved when the material and processing are known and suitable calibration data are available.

Despite the value of residual stresses and the need for such measurements, BN measurement is not currently in wide use in industry. The most widely accepted method now is X-ray diffraction which, although improved in speed and versatility in recent years, is still not readily applicable in complex configurations, and requires removal of covering paint and plating.

The Barkhausen noise method is unusual in that it requires no complicated surface preparation as the X-ray method, is rapid (less than 10 seconds per measurement point), is applicable to complex configurations with the use of special probes, senses very small regions (approximately $0.33cm^2$), and can readily be automated for high speed digital measurement.[14]

III. EXPERIMENTS

3.1. Materials

Two types of steels were used in this research. The first is E911 ferritic heat resistant steel. Second is 15128 steel. The material, which is mainly more investigated and tested among them, was the E911 steel. The chemical composition of E911 is the same as shown in Table 3.1.

E911	C	Si	Mn	Cr	Ni	Mo	V	Nb	W
%	0.12	0.18	0.50	8.80	0.23	0.90	0.20	0.09	0.94

Table 3.1. Chemical composition of E911 steel (wt %)

E911 steel, developed with addition of 1% W to the basic 9%-12% Cr steel, was introduced in the COST 501 European development program to improve high temperature mechanical properties and to extend the range of useful temperature of 9% Cr steels which had been widely used for power plant materials in the 1980s. [15]

Because of the improved high-temperature creep strength quality, this steel is classified as 3rd generation ferritic steel by Masuyama. [16]

For heavy section components such as pipes and headers, minimizing thermal fatigue has been a major driver in addition to achieve high creep strength. For this reason, alloy development has focused on ferritic steels containing 9%Cr. Optimization of C, Nb, Mo, V and W in 9%Cr ferritic steels has resulted in E911. Following in the report of IJPGC, this steel has an even higher allowable stress and can be operated up to steam temperatures of 620℃. From the creep strength point of view, E911 is limited to 593℃. The high temperature properties are essentially same in the two type ferritic and austenitic steels except for oxidation quality. Because of this reason, ferritic steels are widely applied for power plant materials. [17]

It is even reported that this steel is used as the equipment material in high temperature gas cooled reactors. [18]

Table 3.2 shows power plants in Europe where the type E911 steels have been used recently. [19]

Power Plant	Material	Component	Steam conditions ℃/MPa	Installation
Schkopan Unit B	E911	Bendhot, Reheat	560/7	1996
Staudinger Unit 1	E911	Bend main steam	540/21.3	1996
Skaerbaek Unit 3	E911	Bend main steam	582/29	1996
VEW	E911	Super heater	650	1998
Westfalen	E911	Steam loop	650/18	1998

Table 3.2. Application of E911 steel in European power plants

Another tested alloy is the steel type 15128. This steel had also been applied for power plant equipment in the Eastern European countries in the past. It is used at lower temperature than the steel type E911. In this research, two types of 15128 samples were used. The first type of the tested steel was in operation in Hungarian power plants for 40000 hours (15128K). Second type of this tested steel was in original (received) state (15128E). The chemical composition of tested 15128 steel types is shown in the table 3.3.

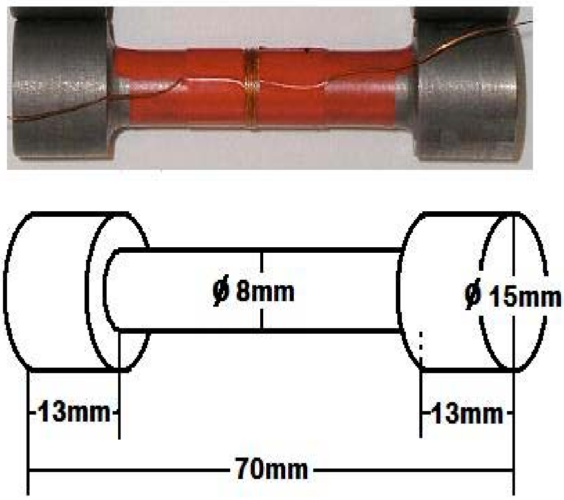
E15128	C	Si	Mn	Cr	Mo	V
%	0.12	0.30	0.70	0.50	0.52	0.33

Table 3.3. Chemical composition of 15128 steel (wt %)

3.2. Specimens and thermal fatigue condition

In total three types of specimen series were prepared. There are two unloaded thermal fatigue types E911 (symbol A in this experiment) and 15128 (symbol E in this experiment). The last type is 15128 (symbol K in experiment), in which thermal fatigue was tested after the steel spent 40000 hours in operation.

Figure 3.1. Shape and size of the cylindrical specimen.



In order to apply repeated thermal fatigue for the system, a special device is used. (See figure 3.2.) This system was designed so that the specimen can be inserted or be picked up with the holder. If the specimen is loaded to the thermal fatigue device (Fig. 3.2.) with the holder, the specimen is fixed by the holder during the thermal fatigue process and thermal strain happens only in the specimen part because the structure of thermal fatigue device is firm enough to ignore the effect of specimen strains. This means the sample is constrained and this condition is very important. In the thermal strain process, if the two ends of the specimen are fixed, the strain does not occur as a result of expansions and contractions but the strain energy is accumulated by each thermal fatigue cycle. This condition is the same as the explanation of strain localization in the theoretical background part.

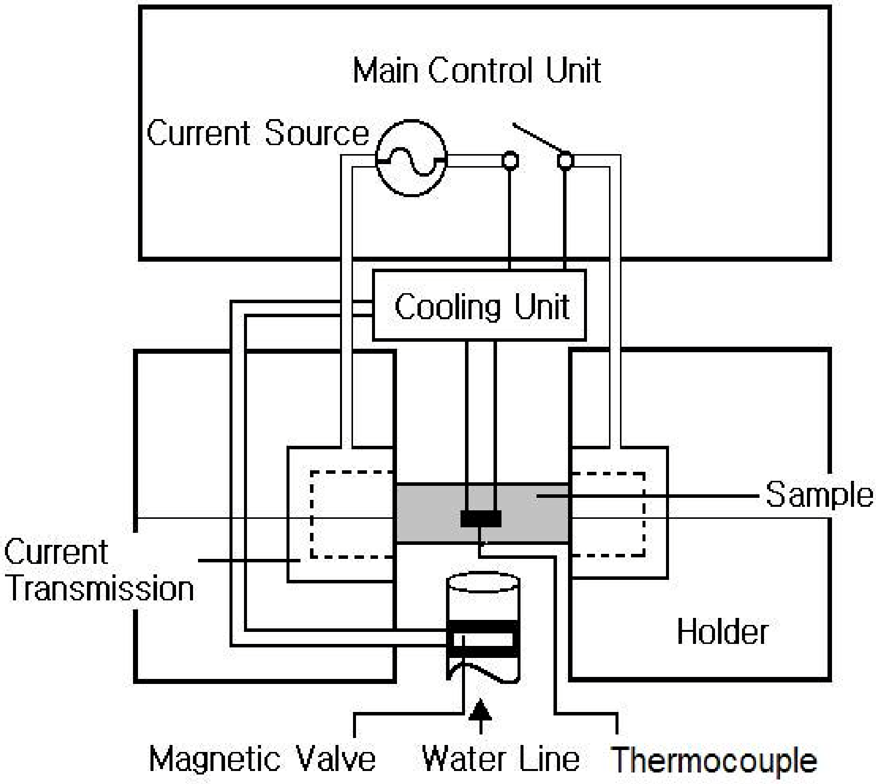


Figure 3.2. Thermal fatigue device

The Joule heat method, which occurs as a result of electric resistance as electric current flows inside conductor, is used in this device. This system is designed so that electric current flows between the two sides of the holder and a thermocouple is contacted to middle point of the sample by spot welding. This thermocouple is the sensor that regulates the heating current.

Two types of temperature determination methods were used. Chromatic thermometer crayons and infrared thermometer were used in parallel.

Figure 3.3 shows the detailed thermal fatigue condition depending on time, temperature and distance of the specimen from the middle point. A thermocouple is welded on the middle point because this is the warmest point of the specimen. The thermocouple works as a sensor to detect temperature. As the temperature reaches 560℃, the main control unit stops the flow of electric current and starts the cooling by opening the magnetic valve of the cooling water tube. In this way, a thermal fatigue cycle is completed and repeated continuously during the test.

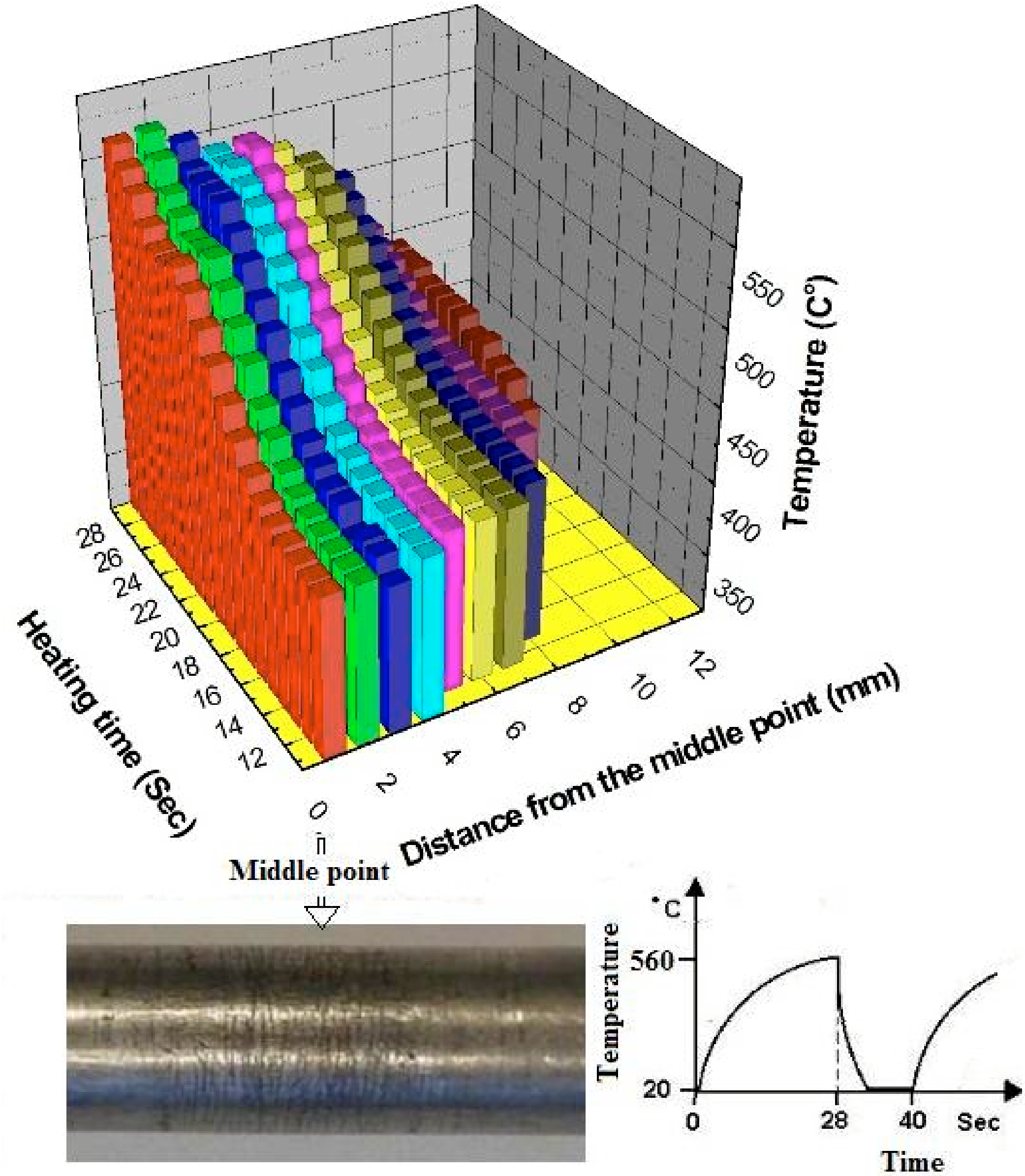


Figure 3.3. Temperatures and heating time variation depending on locations.

3.3. Magnetic methods

3.3.1. Barkhausen noise (BN) and harmonic analysis (HA)

For the BN measurement, some kind of experimental devices are needed. The main part of the BN test system is a solenoid coil to apply an excitation magnetic field and a detector coil to get noise signals. The shape of detector coil or detector head can be changed properly case by case. This is one of the useful properties of the BN test. In this research, two types of detector head or method were used. First is winding the coil directly to the specimen. This method was used for main the BN test in this research. For example, it was used for investigating of the connection between BN and the number of thermal fatigue cycles. Second method is using a detector head containing the same coil. In the case of the BN test depending on the location of the sample the second method was used. In the first case, a detector coil with 50 turns was wound on the cylindrical middle part of the specimens. The specimens were placed in the middle of the solenoidal exciting coil. The coil is excited by sinusoidal 10Hz current source produced by a signal generator and power amplifier. The signal of the detector coil was pre-amplified, digitized and analyzed by a two channel signal-processing unit. The root mean square (RMS) of the noise signal was calculated by computer software to characterize the micro structural changes.

The experimental setting is shown in figure 3.4. This experimental unit was built to measure the BN along the specimen. This is necessary because the temperature of the specimen is not homogeneous during thermal shock fatigue testing. By moving the detector head, the change of the noise can be measured which follows in distance from the middle point of the specimen. Therefore, we are able to analyse the effect of temperature on BN.

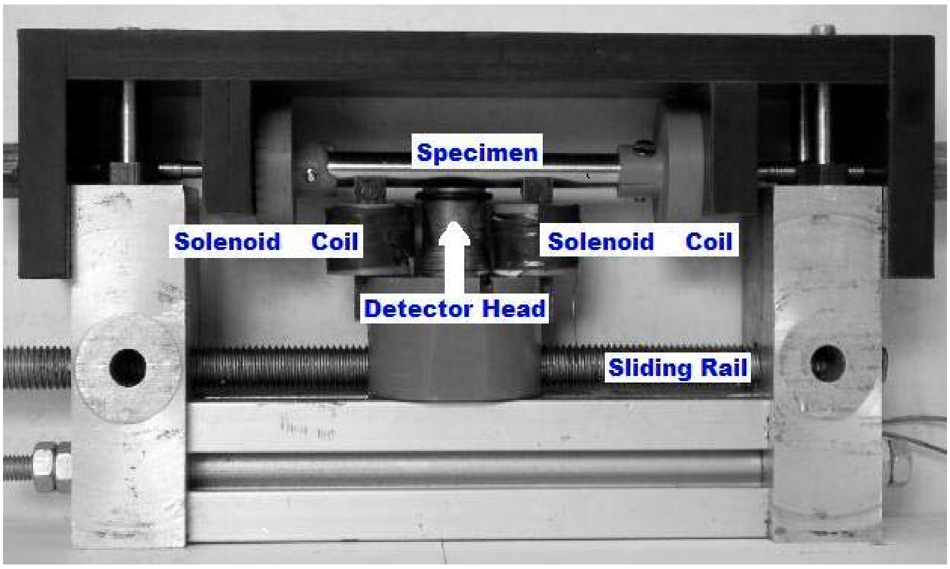


Figure 3.4. Image of second type BN detect tool

In case of harmonic analysis measurements, a special device or tool were not applied. The spectral distribution of the signal of the detector coil was analysed. The spectral analysis was done by mathematical Fourier transformation. Amplitudes of the odd harmonics were investigated as functions of the number of thermal fatigue cycles.

3.3.2. Measurement of coercivity

After measuring BN, specimens were cut to 1.5cm long rods. Coercivity was measured in the portion of the specimen centre, which received the largest thermal fatigue load. The coercivity measurement is a very useful method to characterise the micro structural changes of magnetic materials, but for this measurement one must cut the sample to be placed in the device. This is the reason why it is classified as a destructive method.

3.3.3. Lateral sensitivity of the applied measurements

Because of the different measuring settings the lateral sensitivity of the applied magnetic measurements were different. The following table contains the measured surface area in mm^2..

Signal detecting type	Detecting area (㎟)	Applied measurement
Surface coil (Fig. 3.1)	10x8xπ (cylinder)	BN values depending on the number of thermal fatigue cycles
Detecting coil (Fig. 3.4)	1.5x1.5xπ (circle)	BN values depending on the distance from middle point of specimen
Förster-type	15x8xπ (cylinder)	Coercivity

Table 3.4. Measured surface area depending on applied magnetic measurement.

3.4. Destructive method

3.4.1. Image analysis

The images of the surface and section of the samples were obtained by optical microscope, scanning electron microscope and transmission electron Microscope.

The optical microscope and the SEM were used to investigate the shape of crack on the circumference. Crack images of cross-section and parallel direction of sample were shown.

THESISES

1. It has been proven by the recent research that in case of the steel types E911 and 15128, Barkhausen noise measurement has been successfully applied to detect the changes in microstructure caused by thermal fatigue.

2. BN (RMS) and harmonic amplitude vary with the number of thermal fatigue cycles. BN (RMS) values decrease with the increase of the number of thermal fatigue cycles.

3. In the harmonic analysis of output signals it was shown, that there is a correlation between the amplitude the base and third harmonics and the number of thermal fatigue cycles at the E911 steel type.

4. Coercivity values of the tested steels have a tendency to increase significantly with the number of thermal fatigue cycles. At the steel type E911, the amount of this increase was about 40 percent from the initial state till the final deterioration. The sensitivity of the measurement especially high in the low cycle range, which corresponds to the states of the steels used in power plant constructions.

5. From TEM observation, it was understood that the variation of magnetic properties due to thermal fatigue in the E911 steel type is caused by changing of dislocation density and structure. Especially the subgrain formation and sizes may have influence on the magnetic properties. The subgrain boundaries hinder the domain wall movements, therefore increase the coercivity values and decrease the BN values.