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Matrix replica method and artificial neural networks as a component of condition assessment of materials for the power industry

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ABSTRACT

Purpose: use of matrix replica method and artificial neural networks in condition assessment of materials working under creep conditions. Demonstration of scanning electron microscopy usefulness for correct assessment of the occurrence of internal damages.

Design/methodology/approach: For material after long-term service the microstructural investigations were carried out on metallographic specimens and matrix replicas using light and scanning electron microscope. A computer program was used for material condition assessment.

Findings: The way of material condition assessment by matrix replica method using a computer program as an example of the application of computer materials science methods was presented. The correct development of methodology for assessment of the degree of internal damages in steel working under creep conditions was found a result of verification. Critical comments on condition assessment of structure observed using light microscopy were presented.

Practical implications: The presented method can be used for evaluation and qualification of structural changes in power station boiler components operating in creep conditions.

Originality/value: The presented results of changes in the mechanical properties, structure and in the precipitation processes are applied to evaluation the condition of the elements in further industrial service.

Keywords: Structure; Degradation; Matrix replica; Steel 14MoV6-3; Automatic classification

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MATERIALS

1. Introduction

The statistical data and a number of studies in the power industry explicitly show that the condition of the domestic power industry is to a large extent obsolete. The core of power production is power units built in the years 1970-1990 and having been operated to this day. It needs to be emphasised that due to their working conditions these units were designed for 100,000 hours of service, therefore in the majority of cases they exceeded their design work time, mostly twice, a long time ago, which should be the “energetic retirement”. Therefore not without reason it has been talking in Poland since the beginning of the 21st century about taking actions to provide energy safety, while at the same time meeting the ecological requirements of the European Union. This has forced to take effective actions, which are to a large extent based on maintenance of the current state of electrical power production and construction of new units with supercritical working parameters [17,22,23,24]. In the first case, the accomplishment of the assumed objectives is based on reliable diagnostics of power units that have been being operated for many years, while at the same time taking the renovation works aiming at enhancement of technical and economical indicators by improvement in thermal efficiency from approx. 33-36% to approx. 45%, increase in reliability and availability of the units, reduction in investment and repair costs, and meeting the ecological requirements. In the latter case, i.e. the construction of new units with supercritical working parameters, huge, much higher financial outlays are required. However, based on the analysis of the current condition of the Polish power industry, this seems to be inevitable in the near future, all the more so because it is assumed that hard and brown coal, out of which approx. 95% of electric power is produced in Poland, will be the basic fuel for 50 years to come. Recently, units for supercritical parameters of 464 MW and 833 MW have been put into operation at the Pątnów Power Station and Bełchatów Power Station, respectively. The construction of the unit of 460 MW at the Łagisza Power Station is at an advanced stage. To meet the growing demand for power and ensure safe functioning of the domestic power system, the installed power should be increased by 1000 MW every year. In the years 2013-2015, these requirements can be met in 60% in Poland. In all likelihood, this situation will be improved by renovation and increase in efficiency of the units at the Bełchatów Power Station and Pątnów Power Station, as well as the plans for building 1000 MW units at the Ostrołęka Power Station and in Silesia.

Correct diagnostics of technical condition of critical boiler components plays crucial role in failure-free operation of both the renovated and newly erected power units [4,5,14,18]. It allows determination of their usefulness and time of safe service, qualification for and scheduling of repairs, overhauls and renovations or putting into scrapping.

In diagnostics of components’ material condition the reliable method for assessment of residual life has been searched for many years. However, no single universal method is encountered either in literature or in practice, and the experience so far shows explicitly that a set of research methods and techniques is used for the assessment of residual life [1-3,15,25].

2. Matrix replica method

The matrix replica method, which is subject of this study, is one of the material condition assessment methods. However, the investigations of structure degradation degree and condition of internal damages carried out so far demand that great caution should be exercised when using metallographic methods and determination of relationships between structure condition and material durability. In particular, this concerns the technique of making replicas directly on an object. The material condition assessment requires relevant knowledge of structural changes, internal damages and atlas of structures with assigned exhaustion extents, verified by data from creep tests. Another crucial element required for correct structure assessment is the experience in sample preparation and operation of the equipment used for structure observations. Even a researcher with long-standing experience in interpretation of the condition of structure observed using light microscope may have problems with the assessment of effects from creep voids and carbides, as their contrast is apparently similar. Therefore, to avoid errors in material condition assessment, the scanning electron microscope should be used, as it allows obtaining structure images with high enough resolution, and the range of magnifications should vary between approx. 500 and 5000x. The image mapping procedure by matrix replicas is shown in Fig. 1, while Fig. 2 presents the flowchart of material condition assessment based on structure image.

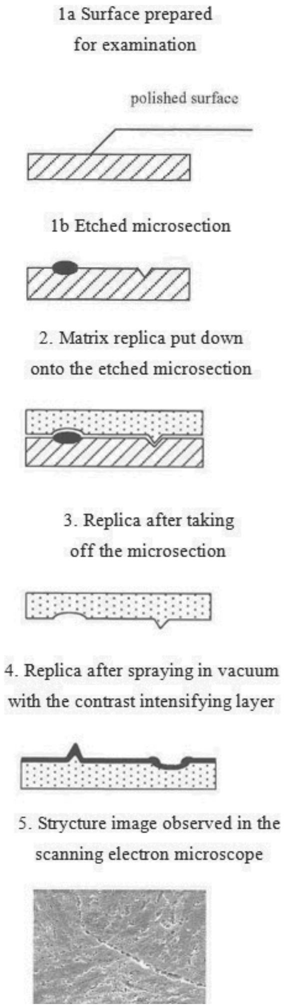

Fig. 1. Image mapping by matrix replicas

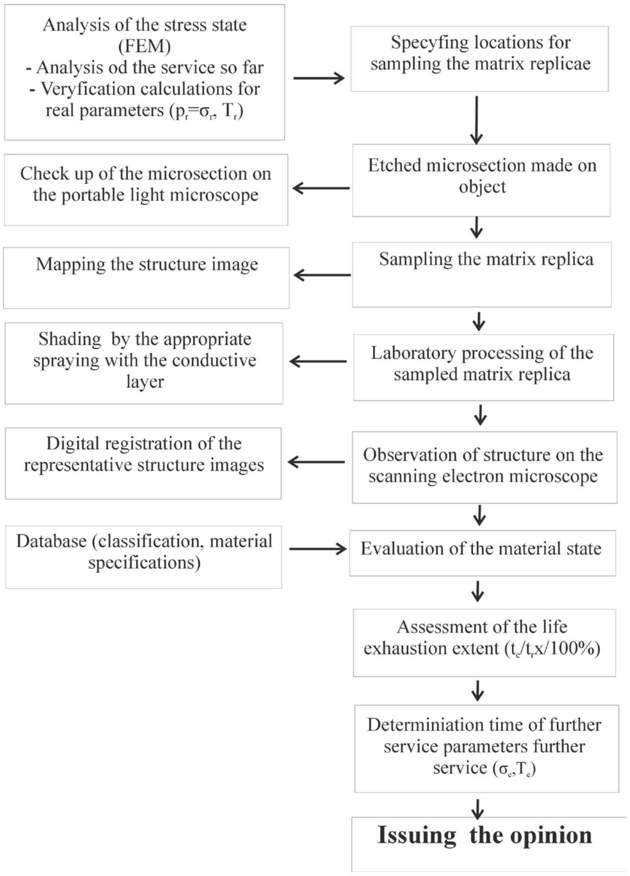

Fig. 2. Material condition assessment based on structure image

3. Application of artificial neural networks in material condition assessment

Artificial neural networks are a versatile tool used for, among other things, selection of engineer materials [6-12], streamlining of manufacturing and technological processes and assessment of the degree of material damage as a result of operation. The authors of this paper developed the methodology for automated computer classification of the condition of internal damages in materials of pressure power system components working under creep conditions to allow the assessment process to be accelerated. In addition, the computer assessment, which has been still improved and tested, is to contribute to the improvement in efficiency of forecasting about the residual life of these materials. Some calculation intelligence systems are also capable of learning, i.e. adapting to changing conditions.

At the stage of program development, the main source of information on the structure of material and changes occurring in it as a result of service under creep conditions is the images of metallographic structures saved as bitmaps with 256 gray shades, obtained mainly by electron microscopy methods [13]. As the existence of internal damages and degree of their advancement within the structure determine material's fitness for further service and is the basis for assessment of further safe service, the material classification model was simplified to five classes characterised by damages specified in Table 1.

The saved images of internal structure damages of low-alloy steels were pre-standardised with regard to their format, scale, contrast and resolution, and then median filtering, decimal-to-binary conversion (at experimentally selected binary level), binary erosion and indexation were carried out one after the other, followed by determination of geometrical and shape coefficients which describe damages summarised in Table 2.

Data from observations of real internal damages were the basis for estimation of interval that values of geometrical factors describing the individual material damages within a specific class and allowing determination of image elements that represent internal damages of material should be in.

Table 1.
Classification of internal damages in materials operated under creep conditions, adopted in the developed model

Class of damages	Type of damages
class 0	structure of initial or similar state with no visible damages
class A	single voids
class B	oriented voids, chains of voids, joined voids, intercrystalline gaps
class C	micro-cracks
class D	macro-cracks

4. Research material

The subject of research was material of the 14MoV6-3 steel primary steam pipeline after service exceeding the design work time with the following parameters: design temperature T_o = 540°C, design pressure = 14.3 MPa. Testing was carried out on two areas selected as a result of non-destructive magnetic particle inspections at the point where surface discontinuities were found. In one case, at the area where cracking preventing a part of the pipeline from further operation was found, sample was taken in the form of a section, which allowed performing metallographic tests on solid material under laboratory conditions.

5. Research scope

The scope of research included non-destructive tests by matrix replica method performed under industrial conditions, and for discontinuity in the form of deep cracking tests were carried out on metallographic microsections. As a part of the work, a computer program was used for material condition assessment to support the automatic classification of internal damages.

For observation of changes within the material structure the light microscope (LM) and scanning electron microscope (SEM) were used. The material condition assessment based on photographs of microstructure taken with light microscope was proved to entail high risk. Therefore, to avoid errors, the scanning electron microscope should be used, as it allows obtaining structure images with high enough resolution, and the range of magnifications should vary between approx. 500 and 5000x.

Table 2.
Determined geometrical and shape coefficients describing internal structure damages of steel after long-term service under creep conditions

Designation	Geometrical and shape coefficients	Geometrical and shape coefficients for which the genetic algorithm makes the least error
Po	area	average area
Ob	circumference	average circumference
Wk	coefficient of roundness	-
Wm	Malinowska coefficient	average Malinowska coefficient
Wc1	coefficient of circularity1	average coefficient of circularity1
Wc2	coefficient of circularity2	average coefficient of circularity2
MinOdl	minimum distance	minimum distance
SFpoz	horizontal Feret diameter	horizontal Feret diameter
SFpion	vertical Feret diameter	vertical Feret diameter
Wz	coefficient of contents	coefficient of contents
MaxOdl	maximum distance	-
Wbb	Blair-Bliss coefficient	-
Wf	Feret coefficient	-
Wh	Haralick coefficient	-
Ws	dimensionless coefficient	dimensionless coefficient

6. Results

6.1. Structure investigation

The microstructure observations of tested material were conducted on matrix replicas and metallographic microsections in 2 areas of the pipeline under investigation. The microsections were prepared by grinding and polishing followed by etching. The microstructure examinations were carried out using light and scanning electron microscope. The examples of obtained structure images of the material under investigation are presented in Figs. 3-6.

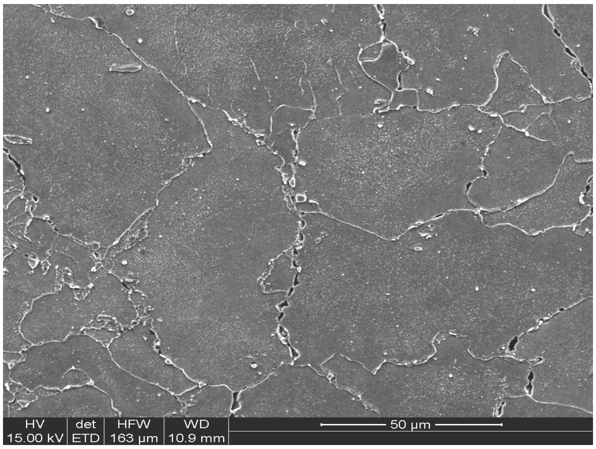

Fig. 3. Structure of pipeline material after long-term service observed on metallographic specimen using SEM

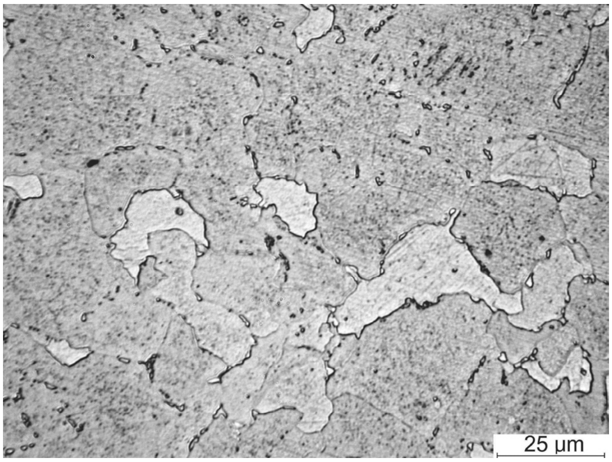

Fig. 4. Structure of pipeline material after long-term service observed on metallographic specimen using LM

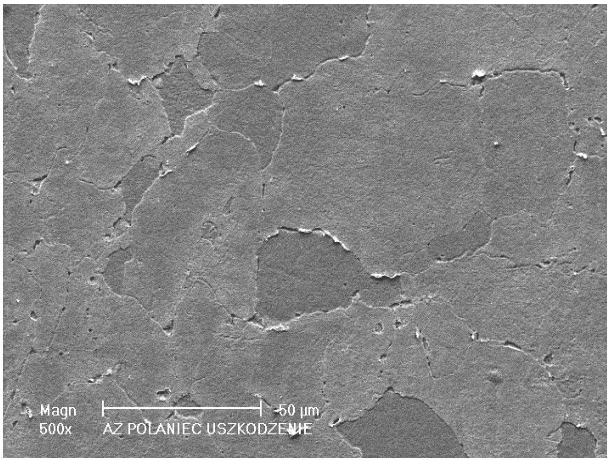

Fig. 5. Structure of pipeline material after long-term service observed on matrix replica using SEM

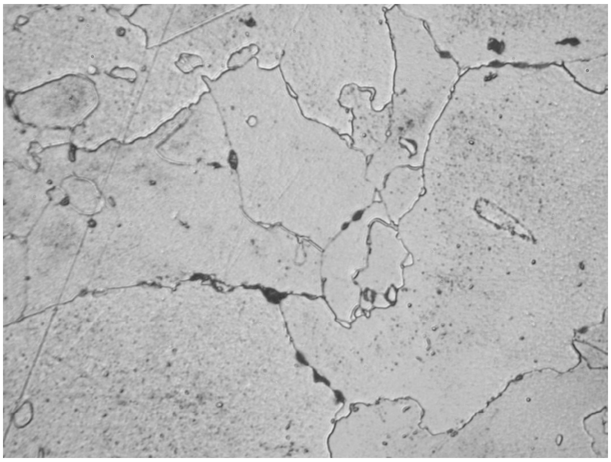

Fig. 6. Structure of pipeline material after long-term service observed on matrix replica using LM

6.2. Computer model

The developed model of computer-aided support of automatic classification of internal damages in steels working under creep conditions using artificial neural networks, genetic algorithms and image analysis is verified experimentally based on test results of real damages identified in steam boiler components.

The calculated values of geometrical coefficients of individual damages were adopted as the input data for development of the material damages classification model. There are five output neurons at the network output, each of them representing a specific class of internal damages. The set of input data consisting of calculated geometric coefficients for 140 experimental cases was divided into three subsets: teaching set (50% of vectors) - used for determination of weight values during the network teaching process; validation set (25% of vectors) - used for network quality assessment made during the teaching process; and test set (25% of vectors) - used for quality assessment of the developed model upon completion of the neural network teaching process [16,20,21].

The genetic algorithms were used for selection of the number and type of input artificial neural networks, while for its optimisation the masks that determine which of the geometrical coefficients should be applied at the network input were used [19].

The network training is based on teaching standards, i.e. input vectors consisting of geometrical coefficients for which the genetic algorithm made the least error: Po, Ob, Wc1, Wc2, Wm, MinOdl, SFpoz, Fpion, Wz, Ws.

The MLP 10-31-5 artificial neural network used in this case allows correct classification of these damages at the level of 93%. The highest damage classification error (8.33%) was found for class B. The result obtained with use of the computer model is structure images observed on metallographic specimen using SEM of the material under investigation presented in Fig. 7-11, which were assigned to individual classes presented in Table 1.

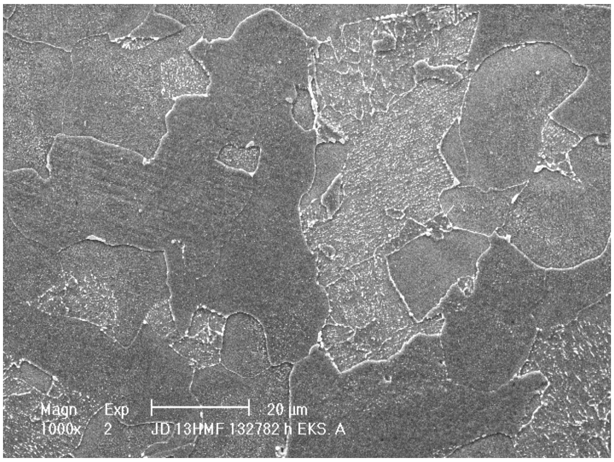

Fig. 7. Structure of pipeline material after long-term service rated at class 0 observed on metallographic specimen using SEM

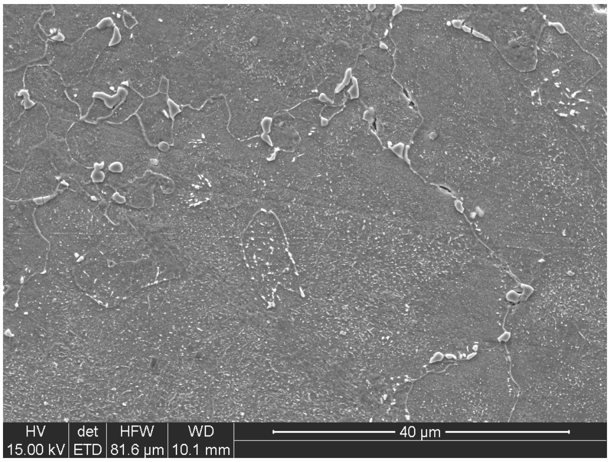

Fig. 8. Structure of pipeline material after long-term service rated at class A observed on metallographic specimen using SEM

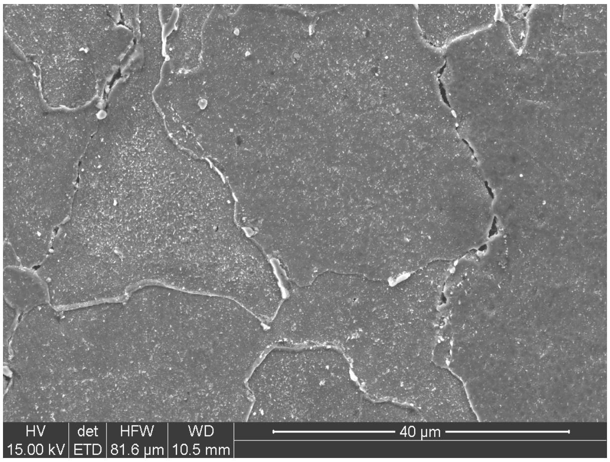

Fig. 9. Structure of pipeline material after long-term service rated at class B observed on metallographic specimen using SEM

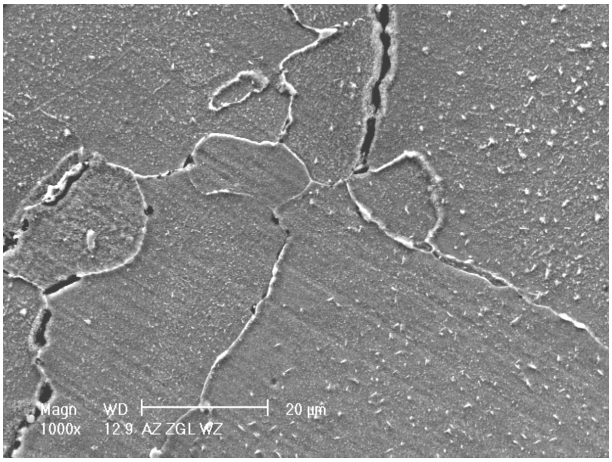

Fig. 10. Structure of pipeline material after long-term service rated at class C observed on metallographic specimen using SEM

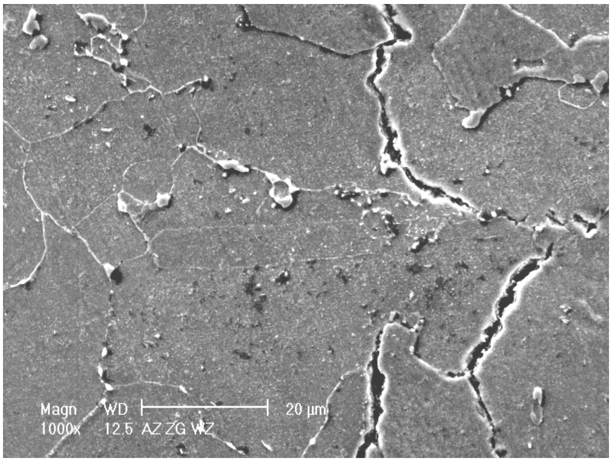

Fig. 11. Structure of pipeline material after long-term service rated at class D observed on metallographic specimen using SEM

7. Conclusions

In the matrix replica method, the scanning electron microscope should be used for material condition assessment as it allows obtaining structure images with high enough resolution and range of magnifications. The elements of extreme importance are the researcher's experience in interpretation of the condition of observed structure and precise handling in accordance with the flowchart presented in this study.

The artificial intelligence methods can be very efficient as calculation tools for solving tasks that typical computers and programs cannot deal with.

In the presented model of computer-aided support of automatic classification of internal damages in steels working under creep conditions, the best results were obtained when using the MLP 10-31-5 artificial neural network which enables the average correct classification of these damages at the level of 93%.

The analysis of quoted methods revealed the need to use the integrated procedures consisting in combination of the matrix replica method and artificial intelligence methods as a component of condition assessment of materials for the power industry.

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