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Remaining Service Life Evaluation of Nuclear Power Plants Construction Steel Elements

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Abstract. The paper is devoted to investigation of S235J2 steel quality criteria variation during thirty years' service life as a part of construction of power-generation unit #1 of Zaporizhia Nuclear Power Plant (NPP). The microstructure of the steel has been evaluated by fractal methods. Fractal size of the steel structure has higher correlation to mechanical properties of the steel compared to microstructure analysis. During service life of the steel YTS ranging 10.01% (24.9 MPa), UTS ranging 9.42% (39.5 MPa), while elongation ranging 43.16% and Reduction of area ranging 39.58%. These values can be explained by strain ageing of the S235J2 steel during service life. It has been stated that fractal size of pearlite and strength have good correspondence (YTS has fractal model correlation coefficient $R^2 = 0.6194$, while UTS has $R^2 = 0.8068$). The correspondence of ferrite fractal size to ductility has been calculated (Elongation has fractal model correlation coefficient $R^2 = 0.6493$ and Reduction of area has $R^2 = 0.5258$). Analysis of the S235J2 quality criteria fractal models let the range quality criteria depends on fractal size of the ferrite-pearlite structure of the steel. Experimental results prove the possibility of usage the fractal models for predicting remaining life of the steel constructions at NPP. Therefore, the fractal modelling may be assumed as a promising nondestructive test method for NPP.

1. Introduction

Remaining service life evaluation of constructions in nuclear power industry is a hard task due to specific maintenance procedure of such constructions [1-3]. Therefore, for investigations of fusion zone reactions and constructions service life predicting widely used the mathematical modelling [4, 5]. One of the promising approach for evaluation of structure transformation due to thermodynamic system parameters is a fractal analysis developed by B. Mandelbrot [6, 7]. The analysis is based on intermediate asymptotic, which is non-integer dimension of an investigated object. Usage of fractal analysis in the materials science let the evaluation of remaining service life of plane parts [8]. Fractal analysis let to range the quality criteria of multiparameter technologies [9, 10], regulate partially incorrect physical metallurgy tasks [11] and evaluate the V. Pareto area [12] for quality criteria of low carbon steels [13].

Analysis of the papers [14-16] prove that fractal formalism can be used for evaluation of remaining service life of cooling pond and reactor shaft parts of power-generation unit #1 of Zaporizhia NPP produced of S235J2 steel.

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2. Materials and methods

The steel specimens were cut off from Cooling Pond (CP) and Reactor Shaft (RS) of the powergeneration unit #1 construction elements. Specimens of steel S235J2 were cut off of from the 6 mm and 4 mm steel sheets. The specimens had sizes:

RS: RS.1 6x240x230 mm; RS.2 4x115x270 mm; RS.3 4x140x270 mm; RS.4 6x185x215 mm; CP: CP.1 6x110x130 mm; CP.2 6x95x150 mm; CP.3 4x82x200 mm; CP.4 4x85x207 mm.

Chemical composition of the specimens has been investigated by spectrum analysis. Each RS and CP specimen has been measured. Average chemical composition of the S235J2 steel is presented in Table 1.

Snaaiman	weight %								
Specifien	Fe	С	Si	Cr	Mn	Cu	Ni	Р	S
CP (mean of 6	98.969	0.20	0.276	0.112	0.520	0.124	0.167	<0.04	<0.04
measurements)	± 0.030	± 0.10	± 0.024	± 0.007	± 0.015	± 0.007	± 0.010	<0.04	<0.04
RS (mean of 6	99.130	0.20	0.266	0.113	0.490	0.110	0.152	<0.04	<0.04
measurements)	± 0.027	± 0.10	± 0.021	± 0.008	± 0.015	± 0.007	±0.010	<0.04	<0.04

Table 1. Chemical composition of the S235J2 steel.

Microstructural analysis of the CP and RS specimens has been performed. Typical microstructure of the CP and RS specimens after 30 years of service inside power-generation unit of NPP are shown on Figure 1 and Figure 2. Analysis of the Fig.1 and Fig.2 shown that steel structure is mostly uniform ferrite-pearlite mixture with some pearlite banding due to hot rolling of the sheets.



Figure 1. Microstructure of the CP3 specimen, collage, x100.



Figure 2. Microstructure of the RS2 specimen, collage, x100.

Any other microstructural constituents (bainite, martensite, etc.) have not been revealed. Nonmetallic inclusions in the structure of RS and CP specimens are fine and cannot be measured by standard scale (Fig.3 and Fig.4). Therefore, it can be concluded that investigated steel S235J2 may be characterized as a clean steel with low density of fine non-metallic inclusions.



Figure 3. Fine non-metallic inclusions in structure of CP3 specimen.



Figure 4. Fine non-metallic inclusions in structure of RS2 specimen.

Pearlite fractal size and ferrite fractal size have been calculated by combined method [17]. The method is based on calculation the mean value of the cell fractal size (based on F. Hausdorff-Безиковича equation [18, 19]) and point fractal size [20].

3. Results and discussion

Calculation of fractal size of ferrite-pearlite structure of CP3 specimen (Fig.5) is presented on Figure 6. For fractal size calculation the microstructure photo has been transformed to black and white mode, where black areas has been identified as pearlite and white as ferrite.







10

Df=1.975

Dфонк Dфонt

11

12

l, pix

As it follows from Figure 4 analysis the best convergence of cell and point pearlite fractal sizes has been occur at image cell cover size l=8 pix, when Dt=(1.986+1.988)/2=1.987. For ferrite structure fractal sizes convergence Dfonk=1.974 and Dfont =1.976 has been occur at tenth iteration step for image cell cover size l=10 pix, when Df is equal to mean value 1.975.

Fractal sizes of all investigated specimens are shown in Table 2.

Journal of Physics: Conference Series

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Sample	Fractal dimension of	Fractal dimension of
N⁰	pearlite, Dt	ferrite, Df
RS.1.1	1.990	1.981
RS.1.2	1.985	1.983
RS.2.1	1.984	1.977
RS.2.2	1.985	1.974
RS.3.1	1.989	1.982
RS.3.2	1.986	1.975
RS.4.1	1.979	1.965
RS.4.2	1.978	1.968
CP.1.1	1.986	1.974
CP.1.2	1.988	1.973
CP.2.1	1.979	1.970
CP.2.2	1.979	1.971
CP.3.1	1.987	1.975
CP.3.2	1.990	1.976
CP.4.1	1.982	1.972
CP.4.2	1.980	1.973
CP.5.1	1.990	1.975
CP.5.2	1.987	1.981
CP.6.1	1.978	1.971
CP.6.2	1.981	1.973

Table 2. Fractal size of microstructure of S235J2 steel.

Where: RS/CP1.1 – longitudinal specimen; RS/CP1.2 – transverse specimen.

Correspondence of structure fractal size to mechanical properties is shown on Figure 5 and Figure 7.



Figure 7. Correspondence of S235J2 steel strength to fractal size of pearlite.

Linear models of strength (Figure 5, a, b) and ductility (Figure 8, a, b) to fractal size of structure prove the response of mechanical properties to structure fractal size.

Journal of Physics: Conference Series

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Figure 8. Correspondence of S235J2 steel ductility to fractal size of ferrite.

Response index K_i calculated as follow [16, 17, 21]:

$$K_i = |Y_i - Y_{i+1}| / |X_i - X_{i+1}|,$$

where $|X_i - X_{i+1}|$ – module of steel quality criteria difference at point *i* and point *i*+1 inside area $i = 1, ..., n; |Y_i - Y_{i+1}|$ – module of fractal sizes difference of the structure at these points.

Ranging of mechanical properties to fractal size of the ferrite and pearlite structure has been made based on calculated response function (Figure 9).



Figure 9. Steel S235J2 quality criteria ranging depends on defining factor.

As it follows from the histogram (Fig. 9) analysis the key parameter is elongation. The elongation has the best response to structure transformation due to ageing of the steel during the service life of the construction. It proved by highest dispersion (43.16%) of elongation values during mechanical ageing of the steel. Therefore, the elongation can be key parameter for construction service life prediction due to high response of the elongation to fractal size of the steel microstructure.

The fractal models of the strength (Figure 7, *a*, *b*) and ductility (Figure 8, *a*, *b*) for S235J2 steel let predict the construction service life without mechanical tests in future. The specimen cut off is complicated procedure due to limited access and high radiation inside cooling pond and reactor shaft.

4. Summary

Remaining life period of the S235J2 steel constructions of Cooling Pond (CP) and Reactor Shaft (RS) of power-generation unit #1 of Zaporizhia Nuclear Power Plant (NPP) has been evaluated by fractal modelling. For fractal modelling next steps have been implemented:

1. Fractal size of pearlite-ferrite structure has been evaluated by original method based on convergence of cell and point fractal dimensions.

2. Fractal models for predicting the mechanical properties of the steel have been created: UTS ($R^2 = 0.8068$), YTS ($R^2 = 0.6194$), Elongation ($R^2 = 0.6493$) and Reduction of area ($R^2 = 0.5258$).

3. Correspondence of the fractal size of the ferrite and pearlite to mechanical properties of the S235J2 steel has been evaluated. It has been obtained that Elongation (39.24) и Reduction of area (35.18) characteristics have best correspondence to steel structure degradation due to ageing during service life cycle.

4. Quality criteria ranging let to define the determinative factor (Elongation) for predicting remaining service life of steel elements based on microstructure degradation.

Experimental results are promising and prove the possibility of fractal modelling for steel constructions service life predicting based on microstructure analysis during steel ageing.

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