Small crack growth in the ODS Eurofer steel

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Abstract. Small crack growth kinetics of the ODS variant of high chromium steel called Eurofer was studied in this paper. The cylindrical specimens of 2 mm in diameter and of 7.6 mm of gauge length were used. A sharp notch of length of 50 μm and semicircular depth profile was prepared in the middle of gauge length using focus ion beam technique. Fatigue tests were regularly interrupted at given number of cycles, notched area was photographed and subsequently the micrographs were analyzed. An exponential dependence of crack length on number of cycles was found. Parameters of Paris-Erdogan law and small crack growth coefficient were determined.

Introduction

One of the most important issues in construction of future fusion reactor is a choice of structural materials. Materials will be exposed to wide spectrum of mechanical or thermal loading including very strong neutron flux originating from plasma reaction. For this reasons, structural materials should keep good mechanical and physical properties to temperatures as high as possible to obtain the highest possible thermal efficiency. Moreover, they should resist to irradiation damage and not to produce radioactive isotopes with long half-time decay. High chromium steels so called RAFM (reduced activation ferritic/martensitic) or RAF (reduced activation ferritic) steels belong to the group of most promising materials. Their properties can be improved by fine dispersion of yttrium oxides (ODS). Basic mechanical properties (tensile, creep, fatigue, brittle fracture and so on) are studied by several groups [1–7].

Fatigue life can be divided into several stages [8]. The stage of fatigue crack growth takes substantial part of fatigue life in most materials; therefore, knowledge of fatigue crack kinetics is a necessity for estimation of residual fatigue life. The well-known Paris-Erdogan law [9] is on of the possibility, but a small scale yielding condition at the crack tip has to be fulfilled. Another approach proposed by Polak [10] offers residual fatigue life estimation based on the small fatigue crack growth kinetics. This approach does not need complicated solution of stress arrangement at fatigue crack tip.

The small fatigue crack growth analysis in the ODS Eurofer steels is presented in this paper and results are compared with its non ODS variant.

Experiment

The ODS Eurofer steel prepared by powder metallurgy steel was produced by the *Plansee Holding AG* in the form of hot rolled plates. The heat treatment applied to material was: annealing at 1100 °C for 30 min, air-cooling and tempering at 750 °C for 2 hours, air-cooling. The chemical composition is given in Table 1.

Table 1. The chemical composition of ODS Eurofer steel in wt. %

Cr	**Mn**	**W**	**Si**	**V**	**O**	**C**	**Ta**	**Ti**	**Y_2O_3**	**Fe**
8.92	0.41	1.11	0.11	0.194	0.201	0.11	0.081	0.33	0.3	rest

The cylindrical specimens of 2 mm in diameter and of 7.6 mm of gauge length with shallow notch in gauge length were used. The notch was mechanically and electrolytically polished. In the middle of this notch, a pre-crack of length of 50 μm was fabricated using focused ion beam (FIB) technique. Parameters of ion beam were set up to obtain a pre-crack with semi-circular depth profile.

A symmetrical cycle was used and total strain amplitude was kept constant during cycling. Strain was measured by an extensometer attached to gauge length. Plastic strain amplitude was determined as a half-width of hysteresis loop in the middle of fatigue life. The fatigue tests were regularly interrupted and micrographs were taken by a light microscope with long focal distance, which was attached to the machine frame. Micrographs were subsequently analysed and a dependence of crack length on number of cycles was obtained.

A typical micrograph taken by light microscope is shown in Fig. 1. The FIB notch can be easily distinguished, the stress axis and crack length are highlighted.

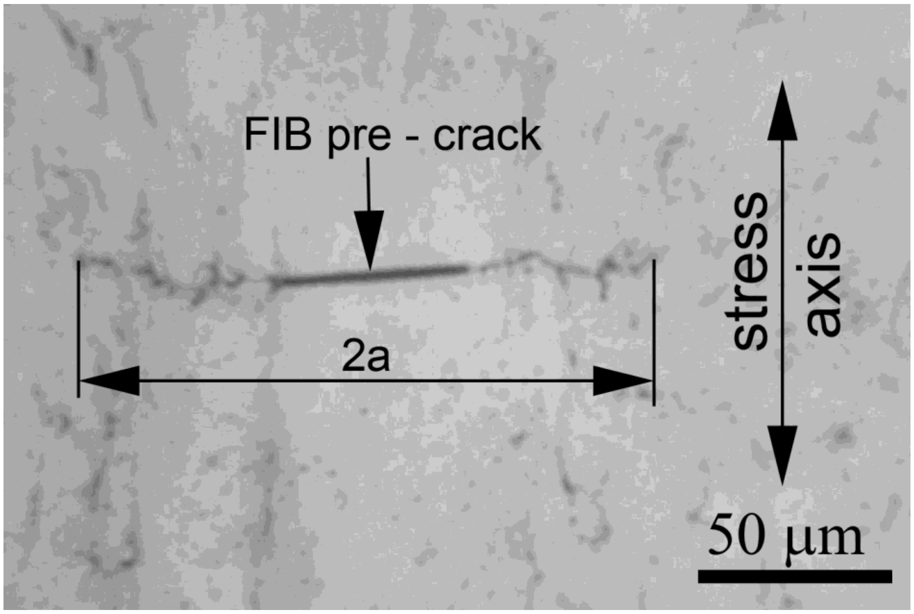

Fig. 1 An optical micrograph of growing crack, N = 7000, ε_a = 0.4 %.

Results

A dependence of crack length *a* on number of cycles *N* for ε_a = 0.5 % is shown in Fig. 2. Obviously, the exponential function fits experimental data very well, which was also observed for others materials [10-13]. This dependence can be described by Eq. 1:

$$a = a_i e^{k_g N} \qquad (1)$$

where a_i and k_g are free parameters of the fit and N is number of cycles. Parameter k_g is called fatigue crack growth coefficient, a_i corresponds to the fictive extrapolated crack length for N = 0. If the exponential law were perfectly valid, then a_i for small N would correspond to the half of the FIB notch length.

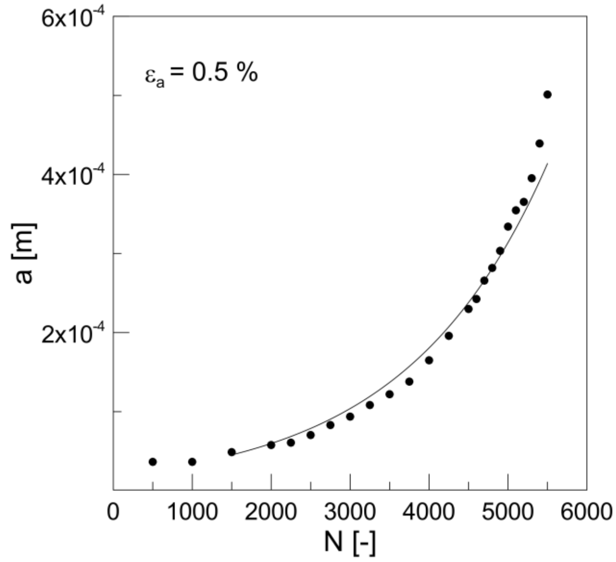

Fig. 2 Crack length as a function of number of cycles, ε_a = 0.5 %, measured data and the exponential fit.

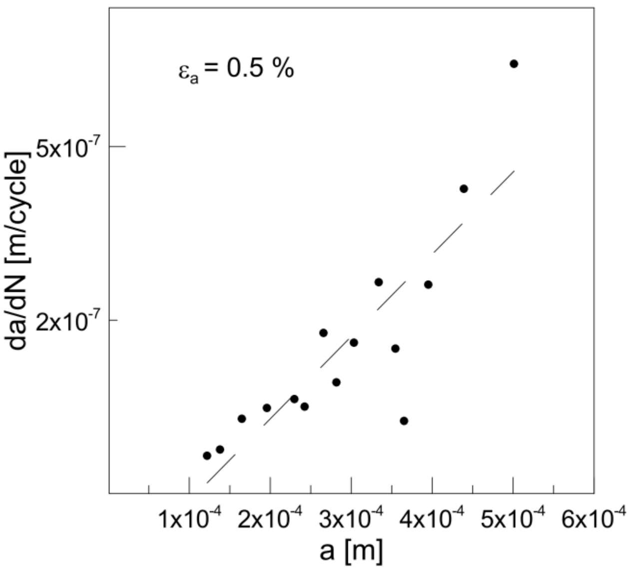

Fig. 3 The fatigue crack growth rate vs. crack length, ε_a = 0.5 %.

In total, seven similar experiments were performed with different ε_a. The Eq. 1 fits experimental data well in all cases. The fitted parameters a_i and k_g are listed in Table 2 together with plastic strain amplitude ε_{ap}. The crack growth coefficient increases with ε_a. The preexponential coefficient varies substantially, which is typical for such analysis.

Table 2. Table of tested specimens

ε_a [-]	**ε_{ap} [-]**	**k_g [-]**	**a_i [-]**
4x10^{-3}	2.5x10^{-4}	4.3x10^{-4}	3.65x10^{-6}
4x10^{-3}	2.35x10^{-4}	3x10^{-4}	
5 x10^{-3}	5.5x10^{-4}	7x10^{-4}	2x10^{-5}
6 x10^{-3}	9.6x10^{-4}	9x10^{-4}	2x10^{-5}
3.7 x10^{-3}	1.3x10^{-4}	2.2x10^{-4}	1.67x10^{-5}
5 x10^{-3}	5.6x10^{-4}	5.9x10^{-4}	1.64x10^{-5}
6 x10^{-3}	1.1x10^{-3}	9.1x10^{-4}	2x10^{-5}

Discussion

The exponential law (Eq. 1) implies that fatigue crack growth rate is a linear function of the crack length (Eq. 2), which is also confirmed by experimental data shown in Fig. 3:

$$\frac{da}{dN} = a_i e^{k_g N} k_g = k_g a \qquad (2)$$

Polák [10] proposed an approach that k_g is a function of plastic strain amplitude and suggested a power law in the following form:

$$k_g = k_{g0}\varepsilon_{ap}^{d} \qquad (3)$$

where k_{go} and d are material parameters. Experimental data were fitted using this formula and parameters were determined as k_{go} = 0.175 and d = 0.75. A comparison of small crack growth kinetics of the Eurofer 97 steel and its ODS variant is shown in Fig. 4. Obviously, the crack growth coefficient is less dependent on plastic strain amplitude in the ODS Eurofer steel than in the Eurofer 97. It seems that the ODS Eurofer steel is more sensitive to lower plastic strain amplitudes than the Eurofer 97 steel and less sensitive to the higher plastic strain amplitude. Nevertheless, the oxide dispersion does not have strong influence on small fatigue crack kinetics in the Eurofer steel. According to published data [10-12] of others ferritic or ferritic/martensitic steels, the exponent d was expected to be equal to 1. This difference can be caused by oxide dispersion or by slightly different microstructure of studied steel, which consists of substantially smaller grains or structural units [6] than in case of other materials.

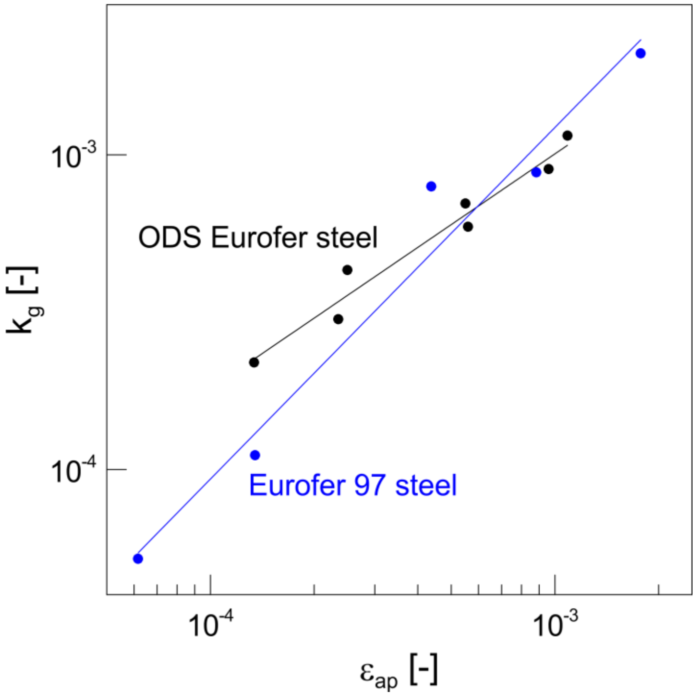

Fig. 4 Fatigue crack growth coefficient as a function of plastic strain amplitude, comparison of the ODS Eurofer steel and of the Eurofer 97 steel [11].

The formula for semicircular crack derived by Broeck [14] was used for calculation of stress intensity factor at the crack tip:

$$\Delta K = 1.12\frac{2}{\pi}\Delta\sigma\sqrt{\pi a} \qquad (4)$$

where ΔK is stress intensity factor range, $\Delta\sigma$ is stress range and a is crack length. Calculated data for three different amplitudes are shown in Fig 5 and it seems that the small scale yielding criterion is probably not perfectly valid. In spite of this fact, Paris-Erdogan law in form given in Eq. 5 for fit was used for:

$$\frac{da}{dN} = C\left(\frac{\Delta K}{\Delta K_0}\right)^m \qquad (5)$$

where C and m are coefficients of Paris-Erdogan law and $\Delta K_0 = 1$ MPa $m^{1/2}$ is introduced in order to keep constant C dimensionless. The slope m varies from 2.48 to 2.91 and constant C from 3.1×10^{-12} to 3.4×10^{-11}. The range of values of m and C is small, nevertheless it is statistically significant. Different approach of fracture mechanics should be used, for example J-integral calculations.

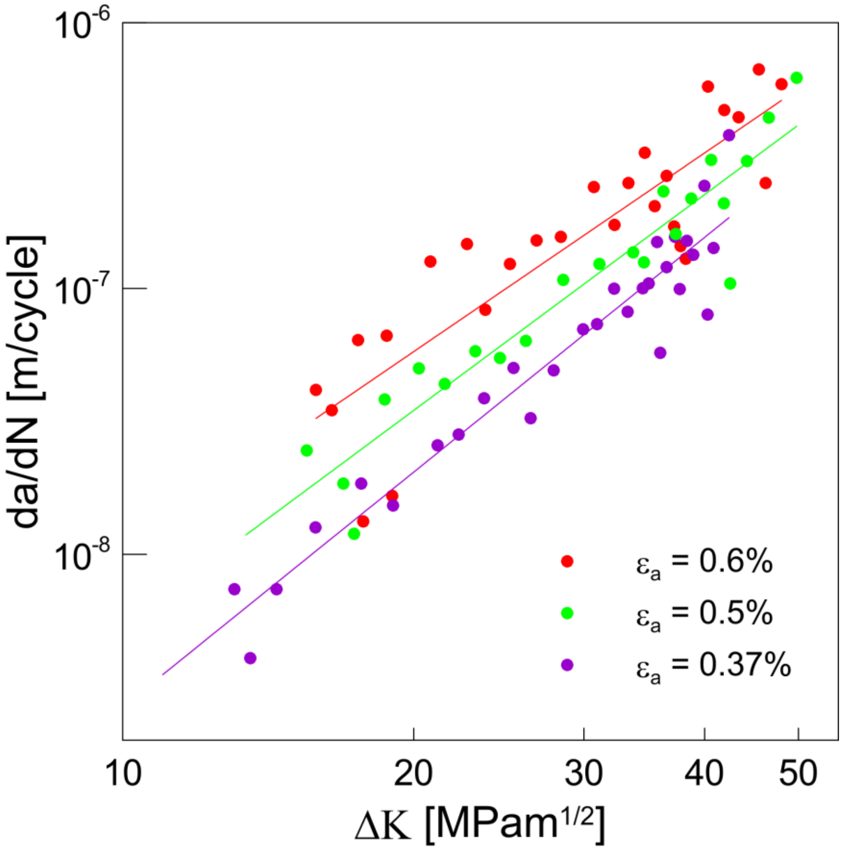

Fig. 5 Paris-Erdogan plot for three different amplitudes.

Summary

The small fatigue crack kinetics of the ODS Eurofer steels was measured. Results can be summarised as follows:

- Crack length increase with number of cycles exponentially.
- Crack growth rate is a linear function of crack length.
- Parameters k_{g0} and $_{\mathrm{d}}$ of Polak's formula were determined as 0.175 and 0.75, respectively.
- Parameters of Paris-Erdogan law were determined and it was confirmed that the small scale yielding criterion is not perfectly valid.

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References

[1] A. Steckmeyer, M. Praud, B. Fournier, J. Malaplate, J. Garnier, J.L. Béchade, et al: Journal of Nuclear Materials. Vol. 405 (2010), p. 95
[2] D.A. McClintock, M.A. Sokolov, D.T. Hoelzer, R.K. Nanstad: Journal of Nuclear Materials Vol. 392 (2009), p. 353
[3] H. Hadraba, B. Fournier, L. Stratil, J. Malaplate, A.-L. Rouffié, P. Wident, et al: Journal of Nuclear Materials Vol. 411 (2011), p. 112
[4] T. Hirose, H. Sakasegawa, A. Kohyama, Y. Katoh, H. Tanigawa: Journal of Nuclear Materials Vol. 283-287 (2000) p. 1018
[5] P. Marmy, T. Kruml: Journal of Nuclear Materiále Vol. 377 (2008), p. 52
[6] I. Kubena, B. Fournier, T. Kruml: Journal of Nuclear Materials. 424 (2012) 101–108.
[7] R. Lindau, A. Möslang, M. Rieth, M. Klimiankou, E. Materna-Morris, A. Alamo, et al: Fusion Engineering and Design. Vol. 75-79 (2005), p. 989
[8] J. Polak, *Cyclic plasticity and low cycle fatigue life of metals* (Elsevier, Amsterdam 1991)
[9] P. Paris, M. Gomez, W. Anderson:The Trend in Engineering. Vol. 13 (1961), p. 9
[10] J. Polák, P. Zezulka: Fatigue & Fracture of Engineering Materials & Structures. Vol. 28 (2005), p. 923
[11] T. Kruml, J. Polák: Journal of Nuclear Materials. Vol. 412 (2011), p. 2
[12] I. Kubena, T. Kruml, J. Polak, in: *6 International Conference on Creep, Fatigue and Creep-Fatigue Interaction (CF-6),* Mamallapuram, India, (2012).
[13] D. Jíša, P. Liškutín, T. Kruml, J. Polák: International Journal of Fatigue. Vol. 32 (2010), p. 1913
[14] D. Broek, *The practical use of fracture mechanics* (Springer, 1989)