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Fatigue crack growth rate of a low carbon microalloyed steel for high temperatures

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Abstract

The influence of temperature on the fatigue crack growth parameter, was analyzed by testing chromium-molybdenum steel of the new generation additionally alloyed with vanadium, designed for high temperatures application. The paper presents a comparison of the fatigue threshold value ΔK_{th} and the fatigue crack growth rate *da/dN* of the specimens taken from the pipe made of virgin steel, tested at room (RT) and operating (HT) temperatures of 540 °C. The influence of the location of the notch and crack initiation, as well as the test temperature, have a decisive effect on the fatigue threshold values ΔK_{th} of the chromium-molybdenum alloyed steel of the new generation additionally alloyed with vanadium for high temperatures application.

Keywords: Fatigue crack growth rate, microalloyed steel, Paris law

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1. Introduction

The development in the study of the behavior of materials under the effect of variable load was made possible by the parallel introduction of experimental and theoretical approaches, because only the theoretical approach cannot fully explain the formation and growth of fatigue cracks. Analysis of the state of stress and deformation at the tip of a growing fatigue crack using linear elastic fracture mechanics methods led to the formulation of the Paris equation for all metals and alloys, which relates the fatigue crack growth rate to the stress intensity factor (SIF) range at the crack tip [1-5]:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \tag{1}$$

Although the Paris equation of crack growth is not valid in the entire region, between low rates near the fatigue threshold ΔK_{th}, and higher rates K_{Ic}, the large linear middle part of the curve covered by the Paris equation turns out to be by far the most important from a practical point of view, as it allows at the same time to contrast between creation and growth of a fatigue crack. The application of the Paris equation has proven to be particularly useful in the field of fatigue of structures made of high strength materials, [6-9].

As the structure under certain conditions will not be endangered until the crack reaches a critical size, it is possible, with previous analyses, to allow the exploitation of the structure with the crack during the crack growth period. Knowing the speed of crack growth and its dependence on the acting load is important information for the decision on further exploitation. Standard ASTM E647-15e1, "Standard Test Method for Measurement of Fatigue Crack Growth Rates" prescribes the measurement of the fatigue crack growth rate da/dN, which develops from an existing crack, and the calculation of the SIF range, ΔK, which means that the specimen should have a fatigue crack.

2. Material details

Research for this work was done on a virgin pipe with an outer diameter of ∅270 mm, length of 275 mm and a wall thickness of ≠34 mm, obtained from the Nikola Tesla B thermal power plant. The chemical properties of analyzed chrome-molybdenum alloy steel of the new generation additionally alloyed with vanadium designed for high temperatures application, are given in Table 1, [10]. Mechanical properties of material tested at RT and HT are shown in Tables 2 and 3, respectively.

Table 1. Chemical composition of as-received steel, % wt.

C	Si	Mn	P	S	Al	Cr	Mo	V
0.12	0.37	0.65	0.01	0.01	0.004	1.042	0.24	0.16

Table 2. Mechanical properties of tested material at room temperature

Elasticity modulus	Yield stress	Tensile strength	Elongation	Poisson's coefficient
E, GPa	$R_{p0.2}$, MPa	R_m, MPa	A, %	ν
197	363	458	26.8	0.3

Table 3. Mechanical properties of tested material at 540 ˚C.

Elasticity modulus	Yield stress	Tensile strength	Elongation	Poisson's coefficient
E, GPa	$R_{p0.2}$, MPa	R_m, MPa	A, %	ν
138	214	300	29.4	0.3

3. Determination of crack growth rate

To determine the fatigue crack growth rate da/dN and the fatigue threshold ΔK_{th} at RT, the standard CT-50 specimen was used, Fig. 1, while the test at HT was performed on the modified C(T) specimens shown in Fig. 2.

Figure 1. CT-50 specimens for fatigue crack growth rate testing at room temperature

Figure 2. Modified C(T) specimens for fatigue crack growth rate testing at high temperature

The tests for the fatigue crack growth rates da/dN as well as the fatigue thresholds ΔKth determination at RT were performed on the servo-hydraulic test machine shown in fig. 3(a). The test was performed in crack growth control. This servo-hydraulic system realizes a sinusoidal variable load in the range of - 100 to + 100 kN.

Testing at HT was done on an electromechanical testing machine shown in Fig.3 (b). The test was performed in position control. Because of the more complete assessment of the behavior of the material under the effect of variable load, and taking into account the dimensions of the specimens, the critical case of the effect of variable load was performed, variable load with stress ratio R = 0.1.

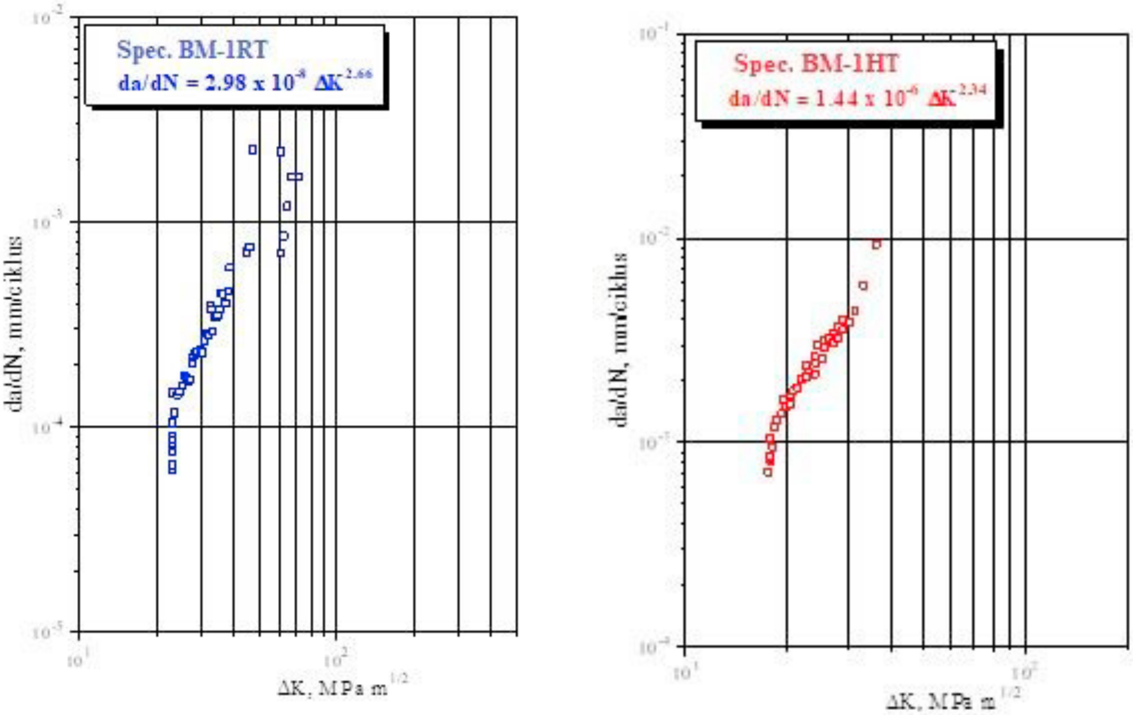
Depending on the applied variable load expressed through the change in the range of SIF, ΔK, curves are drawn in double logarithmic coordinates (log *da/dN* - log(ΔK)). Testing of precracked specimens, the values of the following parameters of the Paris equation were obtained: coefficient C and exponent m, fatigue threshold ΔK_{th}, and fatigue crack growth rate, *da/dN*, at the value $\Delta K = 25\ MPa\ m^{1/2}$. Those results are shown in Table 4. Characteristic diagrams of fatigue crack growth rates, *da/dN* - ΔK, for specimen tested at RT and at a HT are shown in Fig. 4.

Table 4. Fatigue crack growth parameters for specimens with a notch in BM

Specimen	Temperature °C	Fatigue threshold ΔK_{th}, MPa√m	Coefficient C	Exponent m	*da/dN*, μm/cyc, at ΔK=25 *MPa√m*
Spec. BM-1RT		23,2	$2,98 \cdot 10^{-8}$	2,66	$0,253 \cdot 10^{-3}$
Spec. BM-2RT	20	20,4	$2,02 \cdot 10^{-7}$	2,15	$0,303 \cdot 10^{-3}$
Spec. BM-3 RT		19,7	$7,33 \cdot 10^{-7}$	1,85	$0,396 \cdot 10^{-3}$
Spec. BM-1 HT		16,3	$1,44 \cdot 10^{-6}$	2,34	$2,69 \cdot 10^{-3}$
Spec. BM-2 HT	540	15,5	$7,51 \cdot 10^{-6}$	1,89	$3,29 \cdot 10^{-3}$
Spec. BM-3HT		15,1	$4,77 \cdot 10^{-6}$	2,05	$3,50 \cdot 10^{-3}$

(a) (b)

Figure 3. SHIMADZU SERVOPULSER (a) and electromechanical test machine for dynamic tests (b)



(a) (b)

Figure 4. Diagram of da/dN - ΔK dependence of the specimen tested at (a) RT and (b) HT

4. Analysis of results

The influence of the notch position and the initiation of the crack, as well as the test temperature, have a decisive influence on the values of the fatigue threshold ΔK_{th}. Fig. 5. The fatigue threshold values, ΔK_{th}, range from 21.1 $MPa\sqrt{m}$ at RT and decrease to 15.6 $MPa\sqrt{m}$ at HT, Table 4.

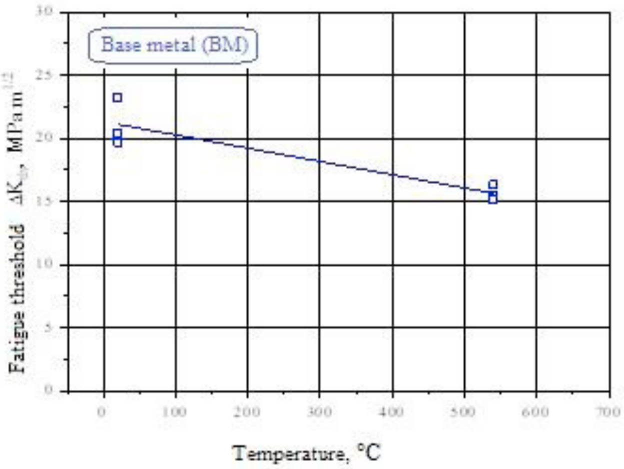


Figure 5. Change in ΔKth value with increasing test temperature

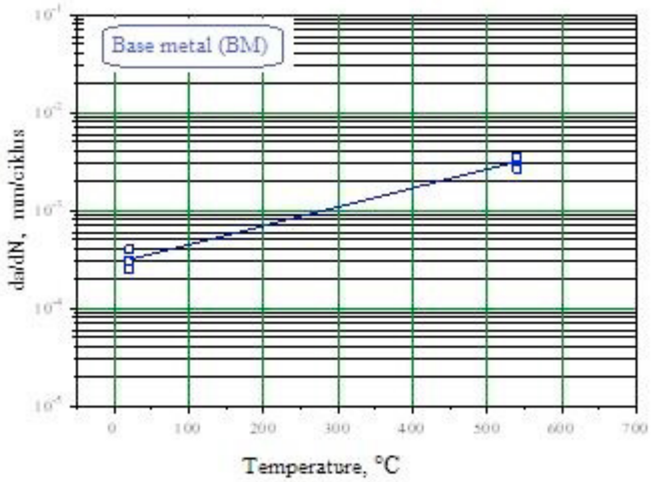


Figure 6. Change in da/dN value with increasing test temperature

The influence of the test temperature on the rate of fatigue crack growth, da/dN, is shown graphically in Figure 6. We can see that with increasing temperature, the rate of fatigue crack propagation, da/dN, also increases. The average obtained value of fatigue crack growth rate at RT is 0.317 μm/cycle, while at HT it is ten times higher and is 3.16 μm/cycle.

5. Conclusion

Mechanical testing of the material and determination of the stress intensity factor at RT and HT showed that the pipe, from which the specimens were taken for the mentioned tests, was made of good quality material that showed good resistance to fatigue crack growth.

Fatigue crack growth parameters are the basis for assessing the safety of the operation of structural elements containing a crack that will not lead to failure in the time period between two consecutive inspections.

A comparison of the fatigue crack growth rate at room and operating temperatures shows that the fatigue crack growth rate of chrome-molybdenum alloyed steel of the new generation additionally alloyed with vanadium for high temperatures application increases with increasing operating temperature.

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