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THE EFFECT OF OPERATING CONDITIONS ON CRACK GROWTH RATE PROPERTIES OF X20 HIGH ALLOYED STEEL

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ABSTRACT
The effect of service temperature and life on fatigue crack growth rate of steel X20 CrMoV 12-1 has been analysed, by testing the new steel and steel after service for 116000 hours. The investigations have included fatigue-crack growth rate at room and operating temperature. These investigations and their analysis provide a practical contribution to assessment of behaviour of high alloy steel X20 under variable loading, thus ensuring safety in operation of the components in thermal power plants.
Key words: High alloy steel X20, fatigue crack growth rate, fatigue threshold

1. INTRODUCTION
The usual service life of processing equipment in thermal power plants operating at elevated temperatures is 30 years, i.e. 150000 operating hours. Economic interests induced extension of designed period, as service life of a large number of the components in power stations is often longer than the designed, indicating the conservatism in design. Therefore, it becomes more and more important to extend service life and to tetrofit the components in thermal power plants, as well as to find the methods to keep the old power stations in operation for 40-50 years, and even longer [1]. Preliminary studies of Electric Power Research Institute (EPRI [2], Centro Elettrotecnico Sperimentale Italiano (CESI) [3] and European Creep Collaborative Committee (ECCC) [4] have shown that the costs of revitalisation of typical thermal power plants can amount to 20-30% of the costs for a new thermal power plant. In such a case, revitalisation means only a guarantee of complete utilisation of life through selective replacement of the components by updated design components. Main item in revitalisation is remaining service life assessment.
Observation of variations in structural materials under service conditions is practically performed during the entire service life, through regular maintenance and emergency overhauls in case that a thermal power plant should be reconstructed and revitalised after failure caused by damage. Observation and inspection of the properties of structural materials of high-temperature loaded components exposed to high pressure, too, in corrosive media are main indicator of their reliability. The most important and comprehensive inspection aimed at establishment of the state of metal in the second half of remaining service life should be performed on expiration of 60% of service life of a component, considering that the probability of crack initated may grow to fracture rapidly. Therefore,

the assessment of remaining life of the components and of the plants is important. As defined, life of a component expires when there is no safety reserve for further use, or when its further use is not economically justifiable [1].

For service safety of structures in processing equipment for operation in thermal power plants, very important properties are those describing the phenomenon of crack initiation and growth under variable loading. Fatigue crack initiation at structurally smooth and homogeneous forms still cannot be described by some simple functions of loading, stress, material properties and cross-section; therefore, empirically derived functions are used, as a rule induced by thorough experimental and laboratory testing. Generally accepted property for that case is fatigue strength that determines the level of loading at which no crack occurs on smooth specimens. Initiation and growth of a crack induced by variable loading, i.e. Paris law of crack growth that establishes the dependence of acting variable loading, of corresponding range of stress intensity factor, and crack growth per cycle is nowadays widely accepted as it generally describes micromechanical behaviour of a growing crack [1].

The effect of service conditions (service life and temperature) on parameters of fatigue crack growth in steel X20 was analysed by testing the new material and material that had been in service for 116000 hours. Testing of new and used steel included determination of parameters of fatigue crack growth rate.

The results obtained by testing and their analysis should provide a practical contribution to assessment of quality of X20 steel, aimed at revitalisation and extension of service life of vital components in thermal power plants made of high alloy steel for elevated temperatures.

2. MATERIAL

For assessment of the effect of service temperature and life on fatigue properties of steel X20 designed for manufacture of vital components in thermal power plants, samples of new pipe (*N*) and a pipe that had been in service for approx. 116000 hours (*U*) were available. Both samples were the pipes ∅450 x 50 mm. Chemical composition of tested pipes is given in Tab. 1 [5].

Table 1: Chemical composition of tested pipe samples

Charge No.	**Chemical composition, mass %**								
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**V**
N	0,21	0,27	0,563	0,017	0,006	11,70	1,019	0,601	0,310
S	0,22	0,31	0,539	0.019	0,005	11,36	1,033	0,551	0,314

3. TEST RESULTS

Main progress in fracture mechanics related to material fatigue is analytical division of the phenomenon of fatigue fracture into period of initiation, during which a fatigue crack nucleates, and period of growth and propagation that follows, during which the nucleated crack grows up to critical size at which rapid fracture occurs. In that way, total number of cycles, N_t, after which fracture occurs, is divided into number of cycles required for fatigue crack initiation, N_i, and number of cycles necessary for it to propagate up to the size critical for fracture, N_p.

$$N_t = N_i + N_p \tag{1}$$

The development in study of material behaviour under variable loading enables parallel introduction of experimental and theoretical approach, as theoretical approach itself cannot completely explain fatigue crack initiation and propagation. The analysis of stress and strain state at the tip of growing fatigue crack using the procedures of linear elastic fracture mechanics (*LEFM*) has lead to formulation of Paris equation [6] for all structural materials, metals and alloys in the first place, that relates fatigue crack growth rate to the range of stress intensity factor at the crack tip:

$$\frac{da}{dN} = C \cdot \left(\Delta K\right)^m \tag{2}$$

Although Paris equation for crack growth is not applicable in the whole region, between low rates near the fatigue threshold (ΔK_{th}) and high rates (K_{Ic}) a large linear central part of the curve covered by the Paris relation has, from the practical point of view, proven to be far most important, as at the same time it allows to make difference between fatigue crack initiation and fatigue crack growth.

Test performed in order to determine fatigue crack growth rate *da/dN* and fatigue threshold, ΔK_{th}, was performed with standard Charpy specimens, using the method of TPB (three-point bending) on resonant, high-frequency pulsator CRACKTRONIC. The test itself was performed as force-controlled. On machined specimens, measuring tape RUMUL RMT A-5 of 5 mm measuring length were attached for monitoring of crack growth using the FRACTOMAT device. As fatigue crack grew under the measuring foil, the later tore following the tip of fatigue crack, thus causing electric resistance of foil to vary proportionally with variation of the crack length. Fatigue crack growth rate was determined based on the obtained functions of crack length, *a* – number of cycles, *N*. Namely, during experiment the number of cycles was automatically registered for every 0.05 mm of crack growth. Obtained curves of dependence *a-N* were used as a base for determination of fatigue crack growth rate, *da/dN*.
To make comparison of the results obtained by testing easier, in Tab. 2 the values of fatigue threshold, ΔK_{th}, coefficient *C* and exponent *m* for fatigue crack growth are given for all tested samples.

Table 2: Results of determination of fatigue crack growth parameters

Sample mark	Testing temperature, °C	Fatigue threshold ΔK_{th}, MPa m$^{1/2}$	Koeficient *C*	Eksponent *m*	*da/dN*, with $\Delta K=20$ MPa m$^{1/2}$
New–1	20	8,1	$1.13 \cdot 10^{-15}$	4.689	$1.42 \cdot 10^{-09}$
New–2	545	6,9	$1.15 \cdot 10^{-13}$	2.933	$7.52 \cdot 10^{-10}$
New–3	570	6,8	$5.72 \cdot 10^{-15}$	3.828	$5.47 \cdot 10^{-10}$
Old–1	20	7,2	$5.84 \cdot 10^{-15}$	4.852	$1.35 \cdot 10^{-08}$
Old–2	545	5,8	$3.09 \cdot 10^{-13}$	3.065	$3.51 \cdot 10^{-09}$
Old–3	570	5,7	$1.80 \cdot 10^{-13}$	3.286	$3.39 \cdot 10^{-09}$

Determination of the dependence of fatigue crack growth rate per cycle, *da/dN*, and range of stress intensity factor, ΔK, is reduced to determination of coefficient *C* and exponent *m* in Paris equation. The range of stress intensity factor, ΔK, depending on specimen geometry and crack length and on variable force range, $\Delta P = P_g - P_d$, should be attributed to fatigue crack growth rate for effective crack length, *a*. Based on the development of testing, $\log da/dN - \log \Delta K$ dependences were calculated and plotted. Typical diagrams of dependence *da/dN* on ΔK are given in Fig. 1 for the specimens taken from new steel X20, and in Fig. 2 for used steel X20.

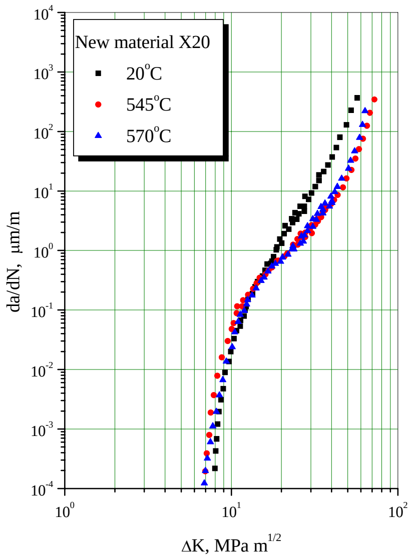

Fig. 1: Diagram of dependence da/dN-ΔK for the specimens taken from new pipes made of steel X20

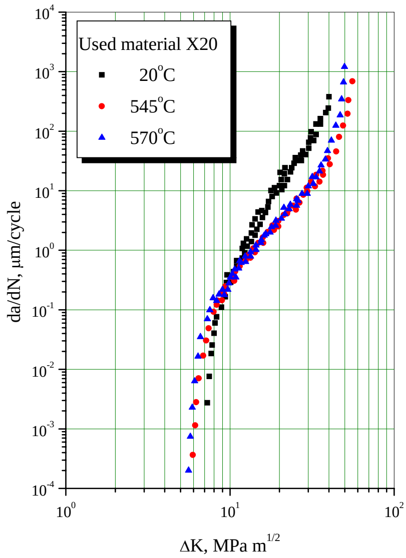

Fig. 2: Diagram of dependence da/dN-ΔK for the specimens taken from used pipe made of steel X20

4. THE ANALYSIS OF RESULTS

As one can see from the results presented in Tab. 2, service time and testing temperature significantly affect the values of fatigue threshold, ΔK_{th}, and parameters of fatigue crack growth. New steel X20 has higher values of fatigue threshold, ΔK_{th}, i.e. better resistance of an already existing crack to propagation. Namely, if new material contains a crack of same length as that in used material, its propagation in new material requires higher loading (range of stress intensity factor, ΔK) for re-growth of the crack.

The samples tested at room temperature have highest fatigue crack growth rate, i.e. the lowest resistance of crack to propagation. Crack propagation resistance increases in the samples tested at operating temperature of 545°C, and the highest crack propagation resistance is encountered in the samples tested at peak operating temperature of 570°C. Under same variable loading (range of stress intensity factor, ΔK), new material X20 has higher value of fatigue threshold and lower fatigue crack growth rate than used material.

One can calculate fatigue crack growth rate for different values of the stress intensity factor range, ΔK. For the analysis, the value of ΔK =20 MPam$^{1/2}$ is taken This value of the stress intensity factor range is located in the part of the curve where Paris law applies. Fatigue crack growth rate, *da/dN*, ranges from 1.42 10^{-9} for the sample of new steel X20 tested at room temperature to 5.47 10^{-10} μm/cycle for the sample tested at peak operating temperature of 570°C. Same tendency toward variation of fatigue crack growth rate applies for used steel.

5. CONCLUSION

Based on the presented consideration, one can conclude that:

- Testing temperature also affects the values of permanent fatigue strength: it decreases with increase of testing temperature. The specimens tested at room temperature have the highest fatigue crack growth rate and the lowest resistance to crack propagation. Crack propagation resistance increases with increase of testing temperature.

Maximum crack growth rate may be expected for the stress intensity factor range approaching to plane-strain fracture toughness K_{Ic}, as at that level brittle fracture occurs. It means that crack growth rates at which fatigue process shall be replaced by development of brittle fracture at various levels of loading can be assessed introducing these values into obtained *da/dN*-ΔK diagrams.

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