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EXPERIMENTAL INVESTIGATIONS OF THE INFLUENCE OF TEMPERATURE AND EXPLOITATION TIME ON THE FATIGUE CHARACTERISTICS OF X20 STEEL

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Abstract: *Research in this paper included the influence of the exploitation period and temperature on high-cycle fatigue properties, as well as fatigue crack growth parameters of the base material steel X20, by testing the new material and material after service for 116000 hours. The obtained test results and their analysis should provide a practical contribution to the assessment of the base material steel X20, thus enabling safety during exploitation of the thermal power plant components in variable load and high temperature conditions.*

Keywords: *high alloy steel X20, permanent dynamic strength, fatigue crack growth rate, fatigue threshold*

1. INTRODUCTION

Exploitation life of the process equipment in the thermal power plants working in the high temperature conditions is up to 30 years, respectively 150000 working hours. Economic interests have influenced the design period, since exploitation life of the large number of components in power plants is usually longer than design life, which indicates the existence of conservatism in design. Due to this, the significance of the extension of the design life and revitalization of the thermal power plant components have increased, as a way to keep older power plants working for 40-50 years, and even longer [1]. Preliminary studies conducted at the Electric Power Research Institute (EPRI) [2], Centro Elettrotecnico Sperimentale Italiano (CESI) [3], and European Creep Collaborative Committee (ECCC) [4] show that the price of the revitalization of the typical thermal power plants can reach 20 to 30% of the price of the new power plant. In this case, revitalization indicates only insurance of the complete effectiveness of design life by means of selective substitution of the components with more modern ones. The basic approach in the revitalization process is the assessment of the remaining design life.

One of the most commonly used steel for operating at high temperatures and high pressures, and at the same time resistant to corrosion, is steel X20 CrMoV 12-1 (hereinafter: X20), primarily intended for the steam lines and pipelines in the thermal power plants because of its strength and toughness at high temperatures. The tendency for the steam line wall to be as thin as possible for the required steam pressure, can only be achieved with the steel of the equivalent characteristics.

For construction exploitation safety of the process equipment in the thermal power plants, the most important characteristics are the ones that describe crack initiation and crack growth under variable load conditions. The occurrence of fatigue cracks on smooth and homogeneous construction shapes is still not describable with simple load and stress correlations, material characteristics and cross-section size, so that empirically deduced correlations have to be applied, conditioned by the extensive experimental and laboratory testing. Generally accepted characteristic in this case is fatigue strength that determines a stress level at which crack does not occur on the smooth test tube. Crack initiation and growth caused by the variable load, i.e. Paris crack growth law that establishes the correlation of the acting variable load, or equivalent stress intensity factor range and crack growth per cycles, is today generally accepted since it describes micro-mechanical behavior of the crack growth [1].

The effect of service conditions (service life and temperature) on high-cycle fatigue properties as 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

- determining fatigue strength and design of the Veler curve, and
- determining fatigue crack growth parameters.

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. EXPERIMENT

2.1. Material

In order to assess the influence of the exploitation temperature and time on dynamic characteristics of the X20 steel intended for design of vital thermal power plants components, we used new tube sample (**N**) and tube sample exploited for 116000 hours (**S**). Both samples were tubes with ∅450x50mm size. The chemical composition of tested steel is given in Table 1, and mechanical characteristics are given in Table 2. [5].

3. TEST RESULTS

3.1. Testing with variable load

The influence of the exploitation conditions on the steel X20 base material in variable load conditions was performed on the sample of new material and material exploited for 116000 hours. These tests were performed in order to determine points in S-N diagram (Veler curve design) and dynamic strength S_f. Test specimens were shaped and sized according to the Standard ASTM E466 [6], Fig. 1. Testing was performed on the AMSLER high frequency pulsator.

Table 1. Chemical composition of the tested tube samples [5]

Batch	**% mass**								
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**V**
Sample - N	0,21	0,27	0,563	0,017	0,006	11,70	1,019	0,601	0,310
Sample - S	0,22	0,31	0,539	0.019	0,005	11,36	1,033	0,551	0,314

Table 2. Mechanical characteristics of steel X20 [5]

Samples mark	**Testing temperature, °C**	**Yield strength $R_{p0,2}$, MPa**	**Tensile strength R_m, MPa**	**Elongation A, %**
New base material				
BM - 1 - 1N	20	521	742	17.3
BM - 1 - 2N		516	738	17.9
BM - 1 - 3N		513	734	18.2
BM - 2 - 1N	545	239	307	18.6
BM - 2 - 2N		231	302	19.2
BM - 2 - 3N		232	306	18.1
BM - 3 - 1N	570	191	249	22.3
BM - 3 - 2N		205	260	21.2
BM - 3 - 3N		196	255	22.7
Exploited base material				
BM - 1 - 1S	20	467	702	16.6
BM - 1 - 2S		471	709	16.4
BM - 1 - 3S		468	707	17.1
BM - 2 - 1S	545	224	281	18.4
BM - 2 - 2S		217	269	18.9
BM - 2 - 3S		220	275	18.1
BM - 3 - 1S	570	179	215	21.5
BM - 3 - 2S		188	231	21.7
BM - 3 - 3S		185	228	20.9

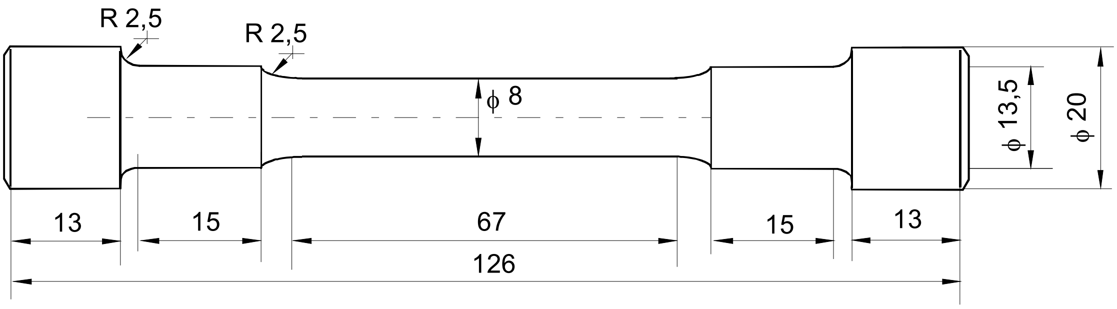

Figure 1. Test specimen for dynamic testing

High frequency pulsator can reach sinusoidal alternate variable load in range from -100 kN to +100 kN. Medium load and load amplitude is registered with precision ±50N. Reached frequency was in between 110-170 Hz, depending on the load quantity and tested temperature. In order to get the complete evaluation of the material behaviour in variable load conditions, and having in mind the test tube size, the most critical instance of variable load was performed, i.e. alternate variable load stress - pressure (R = -1).

The influence of these parameters on permanent dynamic strength values S_f, i.e. maximum dynamic stress at which crack initiation in smooth construction shapes does not occur, is shown in Veler curves (S-N diagrams) in Fig. 2 for new base material tubes, and Fig. 3 for exploited base material tubes.

This testing is determining the number of load changes until fracture occurs during constant range load. A standard demands the data on the size of the load, at which fracture does not occur after certain number of cycles (usually between 10^6 and 10^8 cycles). For steel materials Standard ASTM E468 [7] is defining permanent dynamic strength S_f, following 10^7 cycles. Due to this, the testing is very expensive, but also justified, when data are needed for designing, primarily from the viewpoint of fatigue and fracture mechanics; i.e. when designing components exposed to long-term variable load in total design life of the construction.

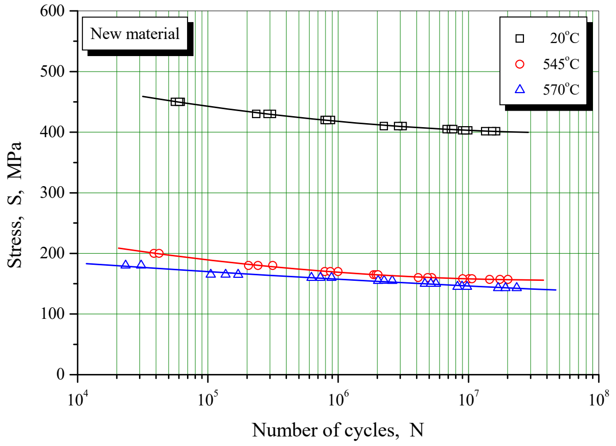

Figure 2. S-N diagram for the new X20 steel pipe base material [5]

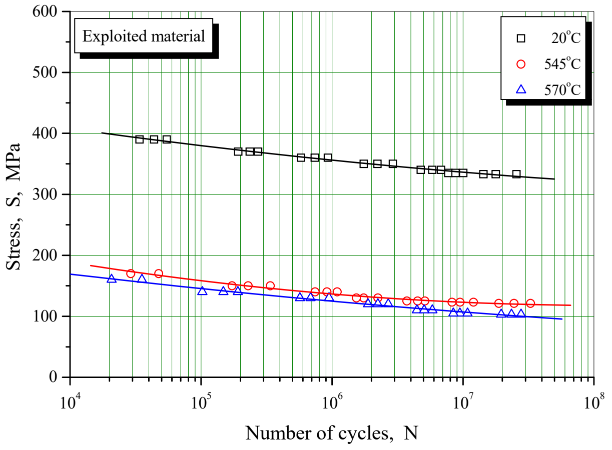

Figure 3. S-N diagram for exploited X20 steel pipe base material [5]

3.2. Determination of fatigue crack growth parameters

The basic progress that fracture mechanics has made in the material fatigue area is in the analytical analysis of the fracture phenomenon during fatigue initiation period in which fatigue crack occurs, but also during consequent growth and expansion period, in which crack grows to the critical size at which a sudden fracture appears. In this way the total number of cycles, N_u, after which fracture occurs, is divided on number of cycles required for fatigue crack initiation, N_i, and number of cycles required for crack to reach size critical for fracture, N_p.

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

Development in material behaviour evaluation in variable load conditions is enabled with parallel experimental and theoretical approach, since only theoretical approach can explain fatigue crack initiation and growth. The analysis of stress and strain at the tip of the fatigue crack growth with linear-elastic fracture mechanics (LEFM) resulted in Paris equation [8] that correlates fatigue crack growth rate and stress intensity factor range at the tip of the crack:

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

Although Paris equation of crack growth cannot be applied in the entire area, in between low rates near fatigue threshold (ΔK_{th}), and high rates (K_{Ic}), large linear middle part of the curve covered by the Paris equation has proven to be the most important since it allows the difference between the fatigue crack initiation and growth.

In order to determine fatigue crack growth rate da/dN and fatigue threshold ΔK_{th}, research was performed on standard Charpy specimen tubes by tube bending method in three points on the resonant high frequency pulzator CRACKTRONIC. The testing was performed in the force control. Measuring tapes RUMUL RMF A-5 with 5 mm measuring length were affixed on the mechanically prepared test tubes that enabled measuring system FRACTOMAT to monitor the crack growth. As fatigue crack grows under the measuring foil, the foil is split following the fatigue crack tip, thus changing electrical resistance of the foil linearly with crack length. Fatigue crack growth rate was determined on the basis of given correlation of the crack length a – number of cycles N. During the experiment number of cycles for each 0,05 mm of the crack growth was automatically recorded. The acquired correlation curves a - N, were used as a basis for the fatigue crack growth rate determination da/dN [8]. For easier comparison of the obtained results, Table 2 provides values of fatigue threshold ΔK_{th}, coefficient C and exponent m of the fatigue crack growth for all tested samples.

Table 3. Results of the fatigue crack growth parameters assessment [5]

Test mark	Testing temp. °C	Fatigue threshold ΔK_{th}, MPa m$^{1/2}$	Coefficient C	Exponent m	da/dN, with ΔK=20MPa m$^{1/2}$
N–1	20	8,1	$1.13 \cdot 10^{-15}$	4.689	$1.42 \cdot 10^{-09}$
N–2	545	6,9	$1.15 \cdot 10^{-13}$	2.933	$7.52 \cdot 10^{-10}$
N–3	570	6,8	$5.72 \cdot 10^{-15}$	3.828	$5.47 \cdot 10^{-10}$
S–1	20	7,2	$5.84 \cdot 10^{-15}$	4.852	$1.35 \cdot 10^{-08}$
S–2	545	5,8	$3.09 \cdot 10^{-13}$	3.065	$3.51 \cdot 10^{-09}$
S–3	570	5,7	$1.80 \cdot 10^{-13}$	3.286	$3.39 \cdot 10^{-09}$

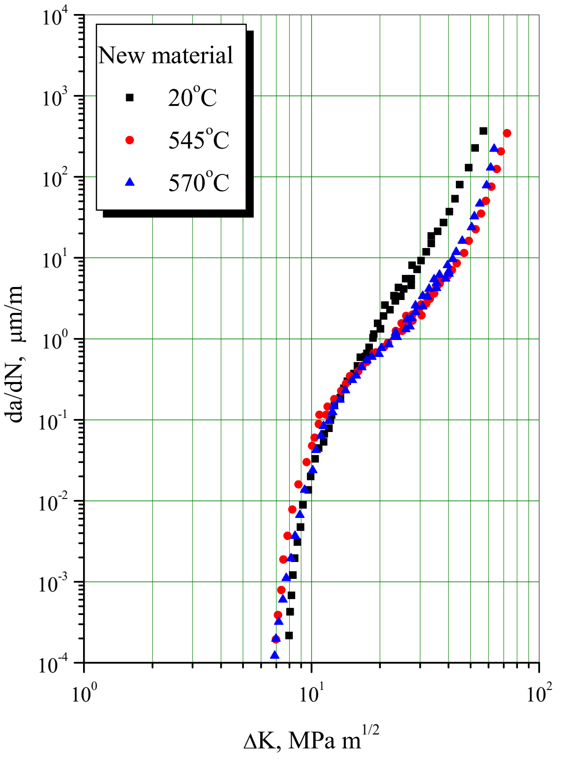

Figure 4. Dependency diagram da/dN - ΔK - test tube of the new steel X20 tube [5]

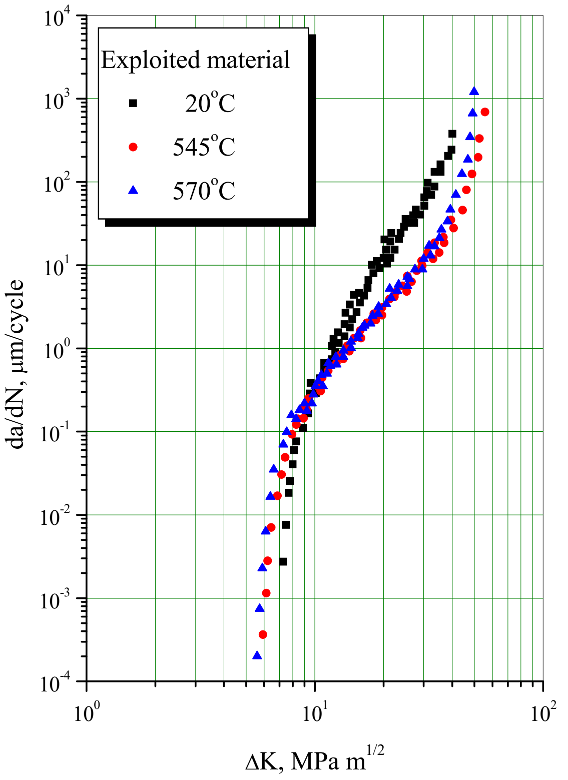

Figure 5. Dependency diagram da/dN - ΔK - test tube of the exploited steel X20 tube [5]

Dependency determination of the fatigue crack growth rate by cycle da/dN and stress intensity factor range ΔK can be reduced to determination of the coefficient C and exponent m in Paris equation. Fatigue crack growth rate requires current crack length, a, and stress intensity factor range, ΔK, that depends upon test tube geometry and crack length, and variable force range, $\Delta P = P_g - P_d$. Based on testing progress, outlined dependencies log da/dN - log ΔK were calculated. Typical dependency diagrams da/dN of ΔK are shown in Fig. 4, for test tubes extracted from new material X20, and Fig. 5, for test tubes extracted from exploited material X20.

4. RESULT ANALYSIS

By analyzing fatigue test results on smooth test tubes with the purpose of designing Veler curve and estimating permanent dynamic strength, we can see that exploitation time and testing temperature greatly affect obtained permanent dynamic strength values. Dependent on the testing temperature in new material tested at the room temperature, we can see that the obtained permanent dynamic strength value is 79% of the yield stress, and in exploited material 71%. During the testing at the operating temperature of 545°C, the obtained value for new material is 65%, and for exploited material 55% of the yield stress value, while at the maximum operating temperature permanent dynamic strength value is 64%, and for exploited material 53% of the yield stress value at the same temperature. If we observe the influence of the load type, we can see that influence of the exploitation time is much higher at dynamic testing, than at static testing [5].

As it is shown in the Table 2, exploitation time and testing temperature have a significant influence on the fatigue threshold values ΔK_{th}, and fatigue crack growth parameters. New material X20 has higher fatigue threshold value ΔK_{th}, i.e. better crack propagation resistance. If new material X20 contains crack of the same length as in the exploited material, its propagation in new material will require higher load (stress intensity factor range ΔK) in order to increase the crack [9].

The highest fatigue crack growth rates, that is, the least crack propagation resistance, have samples tested at the room temperature. Crack propagation resistance is increasing with samples tested at operating temperature of 545°C, while the highest crack propagation resistance can be found in samples tested at maximum operating temperature of 570°C. New material X20 obtained higher fatigue threshold value, and it also acquired lower fatigue crack growth rate in the same variable load conditions (stress intensity factor range ΔK) [10].

We can calculate fatigue crack growth rate for different values of the stress intensity factor range ΔK. The analysis required ΔK value of 20 MPa $m^{1/2}$. This stress intensity factor range can be found in the part of the curve in which Paris Law is applied. Fatigue crack growth rate, da/dN, is moving in the interval of $1.42\ 10^{-9}$ for new material X20 sample, tested at the room temperature to $5.47\ 10^{-10}$ μm/per cycles, for sample tested at the maximum operating temperature of 570°C. The same tendency of the fatigue crack growth rate change can be found in the exploited material.

5. CONCLUSION

Based on the aforesaid, it can be concluded that:

- Exploitation period (new and exploited material) influences the values of the permanent dynamic strength by making new material more resistant to crack initiation in smooth construction shapes.
- Testing temperature also influences values of the permanent dynamic strength. Permanent dynamic strength value decreases with the increase of the testing temperature. Maximum fatigue crack growth rate, that is, the least crack propagation resistance, can be found in samples tested at room temperature. Crack propagation resistance is increasing as the testing temperature grows.

Maximum crack growth rate can be expected at the stress intensity factor range that is close to ductile fracture at flat strain ΔK_{Ic}, because brittle fracture can be achieved on this level. If we enter those values in the given diagrams da/dN - ΔK, it is possible to estimate crack growth rate at which fatigue process gives way to development of the brittle fracture at various load levels.

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