Z. BURZIĆ, DŽ. GAČO, F. ISLAMOVIĆ, M. BURZIĆ, E. BAJRAMOVIĆ

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THE EFFECT OF VARIABLE LOADING ON INTEGRITY OF A WELDED JOINT OF HIGH ALLOY-STEEL X20

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In present paper, experimental investigations have included the effect of exploitation conditions (exploitation time and temperature) on properties of high-cycle fatigue and parameters of fatigue-crack growth of a welded joint of steel X20 CrMoV 12-1 (X20). The effect of exploitation conditions was analysed by testing new pipe and the pipe having been exploited for 116 000 hours. The results obtained by testing and their analysis provide a practical contribution to assessment of quality of a welded joint of steel X20, the aim of which is revitalisation and extension of exploitation life of vital components of thermal power plants manufactured from high-alloy steel for operation at elevated temperatures.

Key words: high alloy steel X20 CrMoV 12-1, welded joint, high cycle fatigue, fatigue crack growth, fatigue threshold

INTRODUCTION

Components of thermal power plants operating at elevated temperatures and high pressures are critical due to specific exploitation conditions. One should also keep in mind that the components of thermal power plants (steam lines, in the first place) in exploitation are exposed to variable loading which, combined with elevated temperatures and high pressures), is actually dangerous threatening to induce damages. Possible failure of these compo-nents would be dangerous not only for operation of the plant, but for environment as well [1].

In case that the damage exists, it is necessary to make an accurate assessment of the component integrity and to make decision on its further exploitation. Preliminary studies [2-4] show that the costs of revitalisation of a typical thermal power plants amount to 20-30 % of the costs of construction of new plants. Therefore, the importance of extension of exploitation life and revitalisation to keep the older thermal power plants in operation has increased.

The aim of investigations within the scope of present paper was to establish as thoroughly as possible the effect of exploitation conditions (exploitation time and temperature) on behaviour of X20 steel welded joints, designed for operation at elevated temperatures under conditions of variable loading. The effect of exploitation conditions on exploitation and structural properties of welded joint of high alloy steel X20 was analysed by testing the new pipe and pipe exploited for 116 000 hours. Tes-ting of the new pipe and exploited pipe made of steel X20 included determination of permanent dynamic strength and construction of Veler's curve, as well as determination of the parame-ters of fatigue crack growth at room (20 °C), operating (545 °C) and maximum (570 °C) opera-ting temperature.

The results obtained by testing and their analysis should practically contribute to assess-ment of quality of a welded joint of steel X20, aimed at revitalisation and extension of exploitation life of the vital components at thermal power plants, made of high alloy steels for operation at elevated temperatures [5].

EXPERIMENTALS

For analysis of the effect of exploitation temperature and time on properties of high-cycle fatigue and parameters of fatigue-crack growth in a welded joint of high alloy steel X20, we had a sample of new welded pipe that had not been in exploitation (*Sample N*) dimensions of which were ϕ 450 x 50 mm and approx. 400 mm long, and a sample of a welded pipe (*Sample E*) dimensions of which were ϕ 450 x 50 mm and approx. 500 mm long sampled from the steam line for fresh steam at a thermal power plant that had been in exploitation approx. 116 000 hours. Chemical composition of the samples of new and exploited pipe has been presented in Table 1. Mechanical properties of the welded joints of new and exploited pipe at room and operating temperatures have been presented in Table 2.

Table 1 Chemical composition of tested pipe samples [5]

Batch	mass %						
	C	Si	Mn	Cr	Mo	Ni	V
Sample N	0,21	0,27	0,56	11,7	1,02	0,61	0,31
Sample E	0,22	0,31	0,54	11,4	1,03	0,55	0,31

Z. Burzić, Military Technical Institute, Belgrade, Serbia.
Dž. Gačo, F. Islamović, E. Bajramović, Technical faculty, University of Bihac,Bihac, Bosnia and Herzegovina.
M. Burzić, University of Belgrade, I.C. Faculty of Mechanical Engineering, Belgrade, Serbia.

Table 2 **Results of tensile tests [5]**

Temperature Testing / °C	$R_{p0.2}$/MPa	R_m/MPa	A/%*	Fracture location
New pipe				
20	518	725	11,6	Basic metal
545	217	294	14,6	Basic metal
570	185	241	15,5	Basic metal
Exploited pipe				
20	472	691	12,4	Basic metal
545	210	268	14,2	Basic metal
570	163	201	15,3	Basic metal

* measured at L_0 = 80 mm, as comparative magnitude (not as material property)

Manual electric arc welding (MEA procedure) using plated electrodes is a fundamental proce-dure of welding for assembling of steel X20, but in most cases, it is necessary to make the root pass and next two to three passes by applying the procedure of welding with non-consumable electrode, i.e. argon-shielded electric arc welding (ASEAW). According to DIN 8575 for steel X20, the wire designated as CM2-1G (old designa-tion SG CrMoWV 1-2) of ϕ 3,2 mm diameter and electrode designated as FOX-20MVW (old designation EKb CrMoWV 12-26 of ϕ 4 mm diameter are recommended. Flow of argon as a shielding gas for ASEAW was 10 l/min, and its purity 99,99 %. Shape of the groove for preparation of welding was chosen based on the diameter and wall thickness of the pipe, according to the procedure MANESMANN [6].

RESULTS AND DISCUSSION

Fatigue of metal is defined as a process of cumulative damaging affected by variable loading, resulting in fatigue-crack initiation and fracture. Strength of a welded joint exposed to variable loading occurring in non-stationary regimes of operation of a steam line during the period of start-up and stoppage (Figure 1) is an important property of exploitation life. Thus one should have in mind that crack-type damages occur after a large number of variations of loading at stresses lower than yield stress (high-cycle fatigue) or after relatively small number of variations of loading (up to 50 000) at stresses close to yield stress (low-cycle fatigue).

At the loading level lower than yield stress typical for high-cycle fatigue, testing is most frequently conducted in rigid mode, i.e. at prescribed stress amplitude. One should keep in mind that the properties of steel X20 substantially vary only at temperatures exceeding 450 °C, which makes these tests reasonable for operating tem-peratures ranging from 545 °C to almost 600 °C for steel X20 [7]

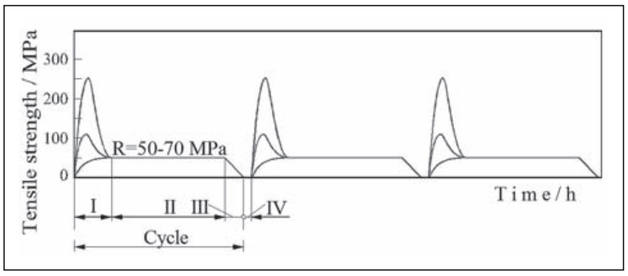

Figure 1 Typical diagrams of stresses of main steam lines at thermal power plants [1]: I – start-up; II – stationary regime; III stoppage; IV - pause

In this test, as a rule, only the number of variations until fracture occurs should be determined under loading of constant range, and the standard requires only information on stress value at which fracture does not occur after certain number of cycles (usually between 10^6 and 10^8 cycles). For steel materials, stan-dard ASTM E466 [8] defines permanent dynamic strength, S_f, after 10^7 cycles. Therefore, this test is necessary when the data are required for design, mainly from the point of view of fatigue and fracture mechanics, i.e. when the parts exposed to long-lasting variable loading during whole projected life of the structure, should be designed.

The effect of exploitation time and temperature on the values of permanent dynamic strength, S_f, i.e. maximum dynamic stress at which no crack initiate, is graphically presented in a form of Veler's curves (S-N diagrams): for welded joint of new pipe in Figure 2, and for welded joint of exploited pipe in Figure 3.

Analysing the Veler's curves obtained by testing the specimens of the welded joints of new and exploited pipe, on can see that exploitation time and temperature

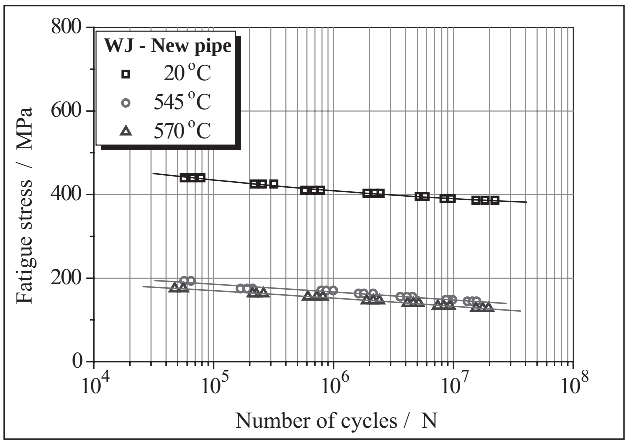

Figure 2 S-N diagrams of the welded-joint specimens of the sample of new pipe made of steel X20 [5]

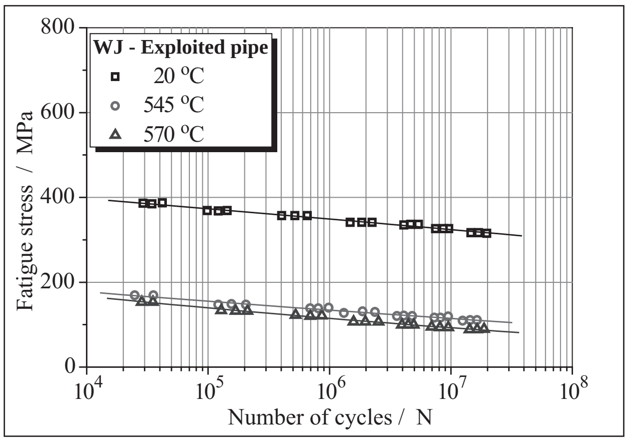

Figure 3 S-N diagrams of the welded-joint specimens of exploited pipe made of steel X20 [5]

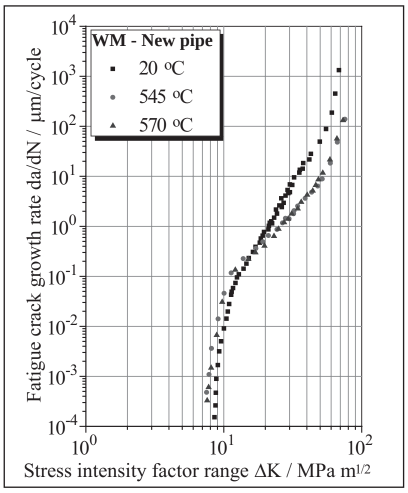

Figure 4 Diagram of dependence da/dN - ΔK for WM specimens of new pipe [5]

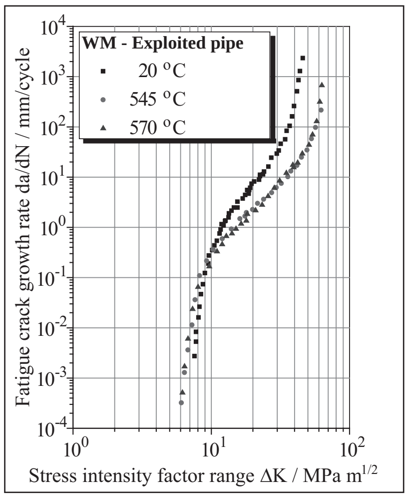

Figure 5 Diagram of dependence da/dN - ΔK for WM specimens of exploited pipe [5]

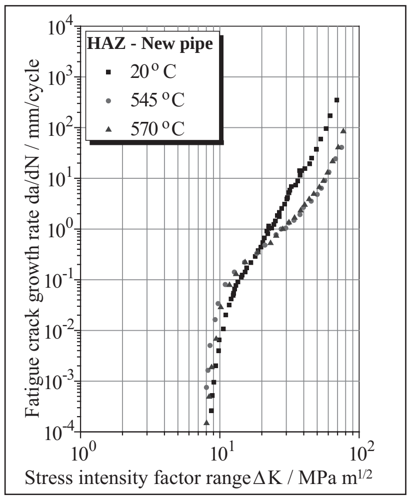

Figure 6 Diagram of dependence da/dN - ΔK for HAZ specimens of new pipe [5]

substantially affect the values obtained for permanent dynamic strength. The values of permanent dynamic strength, S_f, decrease with an increase of testing temperature. Exploitation period of 116 000 hours lead to decrease of the values of permanent dynamic strength, which can be important information if the conditions of steam-line operation are known.

After certain number of cycles, under conditions of variable loading, severe stress concentrators will induce crack initiation and its growth if fatigue threshold, ΔK_{th}, has been exceeded. As the structure under certain conditions will not be jeopardized as long as the crack does not reach the critical value, it is possible to allow exploitation of the pre-cracked structure even during the period of crack growth on condition that it was subjected to preliminary analyses. To make decision on further exploitation, it is essential to know crack-growth rate and its dependence on affecting loading. Standard ASTM E647 [9] defines measurement of fatigue-crack growth rate, da/dN, propagating from the existing crack and calculation of the scope of stress-intensity factor, ΔK.

Testing at room temperature for determination of fatigue-crack growth rate, da/dN, and fatigue threshold, ΔK_{th}, was conducted on standard Charpy specimens, using the method of three-point bending on resonant, high-frequency pulsator. The specimens were mechanically prepared before testing, and on thus prepared specimens measuring tapes were glued for monitoring of crack growth.

Testing at operating temperatures from 545 °C to 570 °C for determination of fatigue-crack growth rate, da/dN, and fatigue threshold, ΔK_{th}, was conducted on modified CT specimens on high-frequency pulsator. The test itself was conducted as force-controlled, with the ratio of minimum and maximum loading R=0,1 [10].

Typical diagrams Fatigue crack growth rate da/dN – Stress intensity factor range ΔK, for the specimen with a notch in WM is shown in Figures 4 and 5, and that for the specimen with a notch in HAZ in Figures 6 and 7.

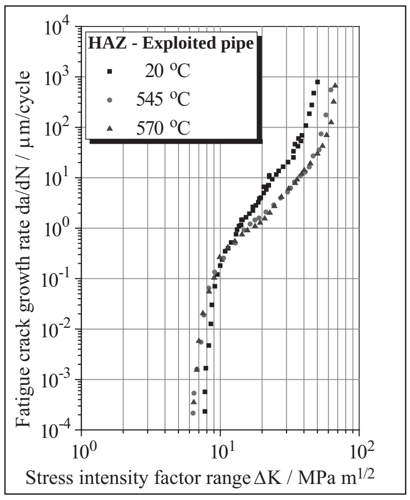

Figure 7 Diagram of dependence da/dN - ΔK for HAZ specimens of exploited pipe [5]

The foundation of the base metal (BM) microstructure of steel X20, Figure 8, is tempered martensite. Between primary martensitic aciculae and at the boundaries of primary austenitic grains carbide precipitates form, most probably $M_{23}C_6$, where M represents alloying elements of steel – most frequently chromium, molybdenum and vanadium [11]. Inside the martensitic aciculae there are no precipitates. Carbides separate mostly at the grain boundaries and near the grain boundaries, and their high temperature stability contributes to high creep resistance of this steel.

There is no substantial difference between weld-metal microstructure of new pipe and exploited pipe, Figure 9. The foundation of weld-metal microstructure is martensite, too, but the size of primary austenitic grains is significantly smaller than that in BM, which means that the length of the austenitic aciculae is also smaller.

In Figure 10, the microstructure of HAZ of a welded joint of new and exploited pipe is shown. Note that pri-

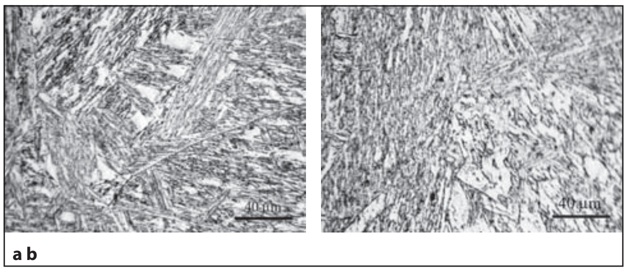

Figure 8 Microstructure of BM of a) new pipe, b) exploited pipe of steel X20

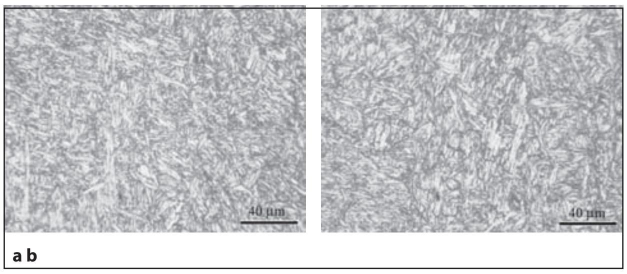

Figure 9 Microstructure of WM of a) new pipe, b) exploited pipe of steel X20

mary austenitic grains in HAZ are coarser in the material that was exploited than in new material.

The size of primary austenitic grains is largest in BM (which is the consequence of steel production) and smallest in WM, which directly affects the size of martensitic aciculae. WM martensite with smaller grain size provides better mechanical properties, ductility and resistance to fatigue-crack growth. Therefore, it is clear why BM is the weakest spot in a welded joint.

CONCLUSION

Based on what has been presented above, one can conclude the following:

The period of exploitation affects the values of permanent dynamic strength in such a way that new material has higher resistance to crack initiation. The value of permanent dynamic strength decreases with increase of testing temperature.

Fatigue-crack growth rate increases with increase of temperature. The specimens with the fatigue-crack tip in HAZ have the highest resistance to growth of the crack already existing in the material. It is obvious that martensite with smaller grain size, predominant in HAZ and WM, provides higher resistance to activation of present crack, which reflects in higher value of fatigue threshold, ΔK_{th}, and lower fatigue-crack growth rate, da/dN.

Exploitation time has the strongest effect on the parameters of fatigue-crack growth, i.e. fatigue threshold, ΔK_{th}. The properties of exploited samples are somewhat inferior, which may be decisive in assessment of integrity and remaining exploitation life of the steam line.

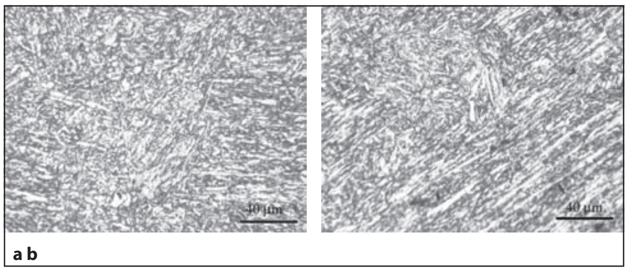

Figure 10 Microstructure of HAZ of a) new pipe, b) exploited pipe of steel X20

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