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THE EFFECT OF VARIABLE LOADING ON THE BEHAVIOUR OF ALLOYED STEEL FOR HIGH TEMPERATURE APPLICATION

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ABSTRACT
For better understanding of initiation and propagation of cracks in welded joints of DIN 13 CrMo 4 4 (JUS Č.7400) steel, aimed for high temperature and high pressure application, it is required to determine the effect of heterogeneity of micro structural and mechanical properties on fatigue crack initiation and propagation. Crack initiation and growth caused by variable loading in the form of Paris law curve is today generally accepted, since it describes micromechanical behaviour of growing crack. Based on the tests, performed with pre-cracked Charpy size specimens, the effect of micro structural and mechanical properties heterogeneity of welded joints on fatigue crack growth parameters is evaluated, using Paris law dependence log(da/dN) - log (ΔK).
Key words: 13 CrMo 4 4 alloyed steel, Paris law, crack propagation, fatigue crack growth rate, threshold fatigue threshold.

1. INTRODUCTION
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.
It is generally accepted that fatigue is the most frequent type of welded structure failures in service. Service behaviour of alloyed steel DIN 13 CrMo 4 4 (Č.7400), aimed for manufacturing of pressure vessels operating at high temperature exposed to high pressure, is greatly depended on the properties of welded joint critical regions, heat-affected-zone (HAZ) and weld metal (WM). Primarily due to their sensitivity to brittle fracture [1].
Welding technology specification of steel 13 CrMo 4 4 plates, 96 mm thick, is defined according to standard JUS EN 288-3 [2]. However, this standard requires neither tests on service temperature (540°C) nor testing of in-service behaviour of parent metal and welded joint at room and service temperatures. The aim of this experiment is to study the effect of heterogeneity of microstructure and mechanical properties on fatigue crack growth parameters *da/dN* and ΔK_{th} of 13 CrMo 4 4 steel welded joint constituents at room temperature and at 540°C.

2. MATERIAL

Available testing coupon was welded joint of 13 CrMo 4 4 steel in size 350x500x96 mm, with double U weld metal in the centre (Fig. 1).

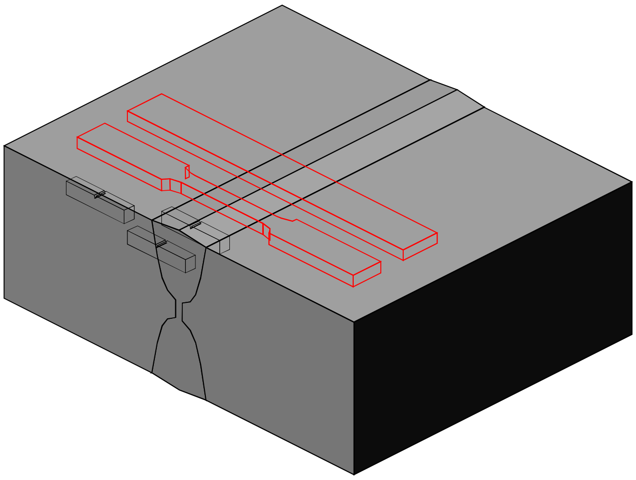

Figure 1. View of testing coupon with double "U" weld and specimens sampling

The plates had been welded by two procedures [3]:

- root passes – by metal manual arc welding (MMA) with covered electrode LINCOLN Sl 19G (AWS: E8018-B2),
- Filler passes – by submerged arc welding (SAW) with wire LINCOLN LNS 150 and flux LINCOLN P230.

3. TESTING RESULTS

Fatigue crack will initiate and propagate from severe stress raisers under variable loading after determined cycle's number if the stress intensity factor range, ΔK_{th}, for fatigue threshold is achieved. The structure can be used before growing crack reaches critical value, based on performed structural integrity analysis. Substantial data for the decision about extended service of cracked component is crack growth rate and its dependence on acting load. Standard ASTM E647 [4] defines testing of pre-cracked specimen for fatigue crack growth rate measurement da/dN, and calculation of stress intensity factor range, ΔK. Two basic requirements in standard ASTM E647 are: crack growth rate above 10^{-8} m/cycle to avoid threshold ΔK_{th} regime, and testing with constant amplitude loading.

Standard Charpy size specimens, pre-cracked in different welded joint regions were tested under variable loading for determination of stress intensity factor range at fatigue threshold, ΔK_{th}, and fatigue crack growth rate da/dN. Testing was performed in load control, by three points bending on high frequency resonant pulsator CRACKTRONIC, Fig. 2.

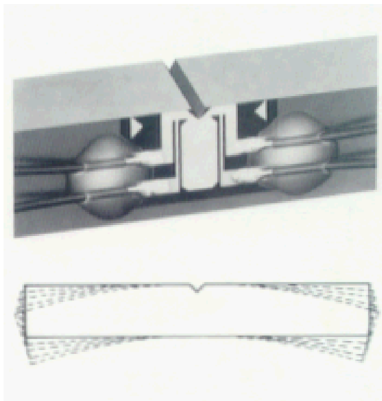

Figure 2. General disposition of RUMUL CRACKTRONIC FRACTOMAT device for fatigue growth rate (left) and view of specimen with cemented foil crack gauge with variable loading bending scheme (right)

This FRACTOMAT device is based on electrical potential measurement, connected with corresponding instruments. For monitoring of crack growth, foil crack gauges RUMUL RMF A-5, 5 mm long, were cemented on the machined specimens, applying the same procedure as for classical strain gauges. Since the foil crack gauge is positioned over the existing pre-crack, it will fracture simultaneously during the crack extension, changing in linear way electrical resistance of the foil.
The dependence fatigue crack growth rate per cycle, da/dN, vs. stress intensity factor range, ΔK, is determined by the coefficient C and exponent m in the equation of Paris [5]. It is necessary for actual crack length, a, to attribute corresponding stress intensity factor range, ΔK, which depends on specimen geometry and variable load range, $\Delta P = P_g - P_d$; Pg is upper; P_d is lower load in a cycle. This relation can be calculated and drawn in the form log da/dN - log (ΔK) based on the test results, performed ate room and service temperature (540°C) [5]. Obtained relations are presented in Fig. 3 for the specimens pre-cracked in based metal (PM); weld metal (WM) and heat-affected-zone (HAZ).

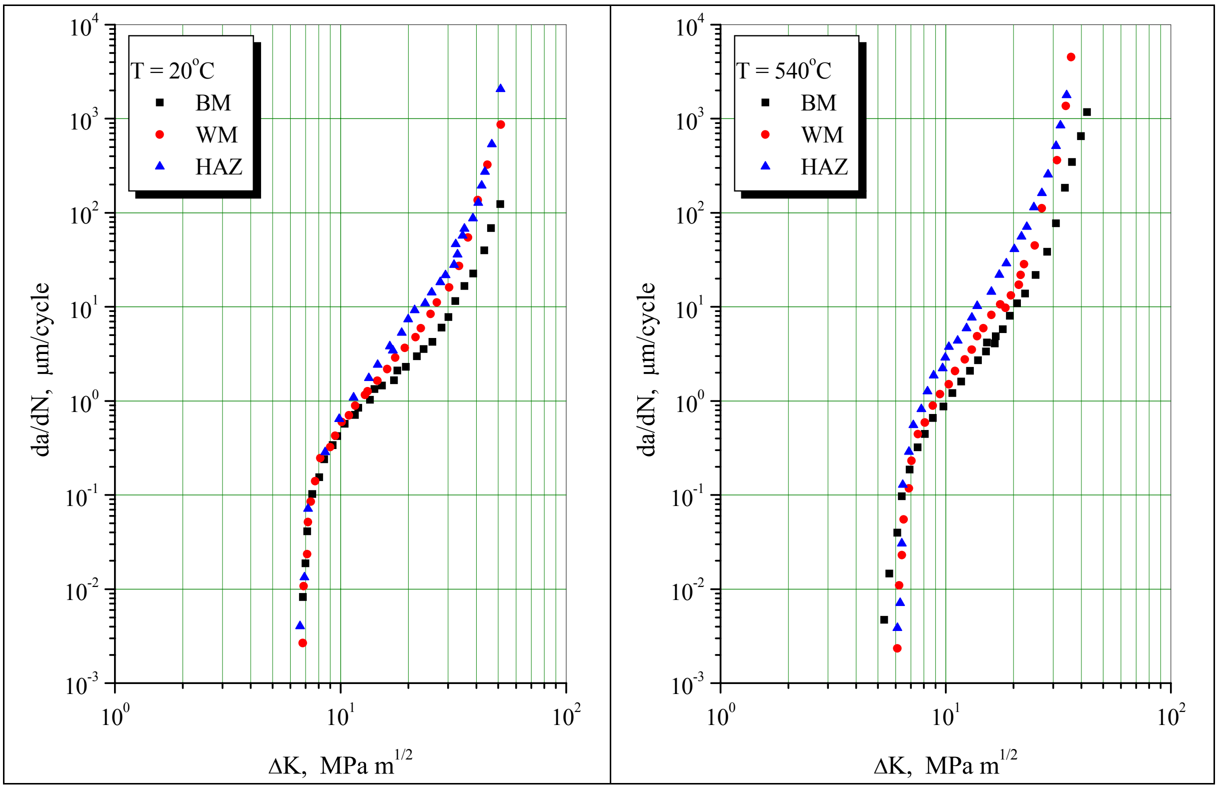

Figure 3. Fatigue crack growth rate per cycle, da/dN, vs. stress intensity factor range, ΔK, specimens pre cracked in BM, WM, and HAY tested at room temperature (left) and at 540°C (right)

Obtained values of coefficient *C* and exponent *m* in the equation of Paris are given in Table 1, together with the values of stress intensity factor range, ΔK_{th}, at fatigue threshold.

Table 1. Parameters of Paris equations (Fig. 3)

Specimen designation	Test temperature, °C	Stress intensity factor range at fatigue threshold, ΔK_{th}, MPa $m^{1/2}$	Coefficient C	Exponent m	Crack growth rate da/dN, μm/cycle at ΔK = 10 MPa $m^{1/2}$
BM–1s	20	6.8	$2.98 \cdot 10^{-13}$	3.62	$1.24 \cdot 10^{-09}$
WM–1s		6.8	$3.88 \cdot 10^{-13}$	3.82	$2.56 \cdot 10^{-09}$
HAZ–1s		6.7	$3.05 \cdot 10^{-13}$	4.01	$3.12 \cdot 10^{-09}$
BM–1p	540	5.9	$3.11 \cdot 10^{-13}$	4.08	$3.74 \cdot 10^{-09}$
WM–1p		6.2	$3.27 \cdot 10^{-13}$	4.14	$4.51 \cdot 10^{-09}$
HAZ–1p		6.1	$3.38 \cdot 10^{-12}$	3.17	$5.00 \cdot 10^{-09}$

4. RESULTS ANALYSIS

Results presented in Table 1 clearly show that crack tip position and testing temperature determine threshold stress intensity factor range ΔK_{th} and fatigue crack growth behaviour. For the comparison, stress intensity factor range $\Delta K = 10$ MPa√m in the portion of Paris law validity in Figs. 3 to 5 is selected. Corresponding crack growth rates at room temperature ranged from $1.24 \cdot 10^{-09}$ μm/cycle for parent metal, to $2.56 \cdot 10^{-09}$ μm/cycle for weld metal and $3.12 \cdot 10^{-09}$ μm/cycle in HAZ, indicating that HAZ is critical constituent in welded joint. At 540°C crack growth rates are significantly higher compared to room temperature ($3.74 \cdot 10^{-09}$; $4.51 \cdot 10^{-09}$; 5,00 10^{-9} for parent metal, weld metal and HAZ, respectively), but with the lower differences in constituents, what can be explained by better ductility at elevated temperature. Again, HAZ is most critical constituent in welded joint.

In spite of significant differences in fatigue crack growth rates, obtained values are still low and acceptable. That means, tested steel and its welded joint exhibited acceptable level of fatigue crack growth resistance and can be successfully applied for variable loading in the case of detected crack-like defect, primarily for low cycle fatigue.

The behaviour of welded joint as whole, as well as of their individual constituents, can be connected with the change in slope of valid portion of Paris curve. In general, materials with lower fatigue crack growth are characterized by lower slope on the diagram da/dN vs. ΔK. Lower crack propagation is confirmed on specimens from parent metal and from weld metal, requiring higher stress intensity factor range for the same crack growth rate. Maximum fatigue crack growth rate can be expected at the level of stress intensity factor approaching to plane strain fracture toughness, the condition for brittle fracture.

5. CONCLUSION

Following conclusions can be derived:

- Decisive effect on stress intensity factor range ΔK and fatigue crack growth parameters can be attributed to the position of machined notch and following initial crack, as well as testing temperature.
- The highest resistance to crack propagation, expressed by minimum fatigue crack growth rate, exibited the specimens pre-cracked in parent metal, and maximum fatigue crack growth rate is found in specimens pre-cracked in heat-affected-zone. This is directly connected with the effect of microstructural heterogeneity of welded joint constituents on fatigue crack growth rate da/dN.
- The behavior of pre-cracked specimens taken from different welded joint constituents (parent metal, weld metal, heat-affected-zone), tested at service temperature (540°C) by variable loading, regarding fatigue threshold and fatigue crack growth parameters, exhibited two to four-fold higher crack growth rate compared to room temperature, what can be explained by reduced properties at elevated temperature.

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