EXPERIMENTAL ANALYSIS OF CRACK INITIATION AND GROWTH IN WELDED JOINT OF STEEL FOR OPERATION AT ELEVATED TEMPERATURE

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ABSTRACT:

In the present paper, experimental investigations have included the analysis of crack initiation and growth in welded joint of steel for operation at elevated temperatures. Based on the tests conducted with pre-cracked CT and Charpy size specimens, the effect of heterogeneity of microstructural and mechanical properties of welded joints on fracture toughness and fatigue-crack growth parameters was determined.

1. INTRODUCTION

Service behaviour of alloyed steel A-387 Gr. 11 Class 1, designed for manufacture of pressure vessels operating at high temperature and exposed to high pressure, is highly dependant on the properties of critical regions of welded joint, heat-affected-zone (HAZ) and weld metal (WM), primarily due to their high sensitivity to brittle fracture. Heat affected zone (HAZ) and weld metal (WM) are potential locations of crack initiation, i.e. the locations where local brittle zones may form to whom crack initiation is ascribed [1].

Welded joint, as an integral part of a structure, has inhomogeneous microstructure and mechanical properties, very often geometry too, and stress field as well, affected by various factors such as residual stresses after welding. However, these fundamental difficulties do not make experimental determination of fracture mechanics, K_{Ic}, impossible under plane strain conditions, either in certain critical regions of a welded joint or a welded joint as a whole, but they do make interpretation of the measured values difficult. Therefore, great interest in application of investigations of fracture mechanics in case of welded joints is natural [2,3].

For better understanding of the cause and mechanism of crack initiation and growth in welded joints of steel designed for operation at elevated temperatures and under high pressures, it is necessary to establish the effect of heterogeneity of the structure and mechanical properties of a welded joint on crack initiation and growth and to quantify the parameters affecting the local strain behaviour and crack growth. The aim of this experiment is to study the effect of heterogeneity of microstructure and mechanical properties on fracture toughness, K_{Ic}, and fatigue crack growth parameters da/dN and ΔK_{th} of A-387 Gr. 11 Class 1 steel welded joint constituents at room temperature and at 540°C [4].

2. MATERIAL

For assessment of the effect of operating temperature on fracture toughness, K_{Ic}, and fatigue-crack growth parameters of A-387 Gr. 11 Class 1 steel, sample of 350 x 500 x 96 mm with double U weld metal in the centre were available. The specimens for qualification of the welded joint, WM and HAZ were machined from a welded sample plate) [5]. The chemical composition and mechanical properties of A-387 Gr. 11 Class 1 steel are shown in Tables 1 and 2, respectively.

Table 1: Chemical composition of tested material [5]

Material	Chemical composition, mass %						
	C	Si	Mn	P	S	Cr	Mo
A-387 Gr. 11 Class 1	0.15	0.29	0.54	0.022	0.011	0.93	0.47

Table 2: Mechanical properties of tested material [5]

Material	Yield stress $R_{p0.2}$, MPa	Tensile strength, R_m, MPa	Elongation, A, %	Impact energy, J
A-387 Gr. 11 Class 1	325	495	35	165

The plates were welded by two procedures [5]:

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

3. RESULTS AND DISCUSSION

3.1 Fracture toughness, K_{Ic}.

Testing of plane-strain fracture toughness of the specimens taken from the welded plate made of steel A-387 Gr. 11 Class 1 was conducted. The aim was to determine critical stress-intensity factor, K_{Ic}, i.e. to estimate the behaviour of basic metal (BM) and components of the welded joint, weld metal (WM) and heat-affected zone (HAZ) in presence of a crack-type defect as the most jeopardizing defect in structural materials, especially in welded joints. The tests were conducted using the three-point bend (TPB) and CT specimens, geometry of which is defined by the BS 7448-Part 1 standard [6]. Three-point bend (TPB) specimens were used for testing at room temperature. Due to specific design of the chamber, CT specimens were used for testing at operating temperature of 540°C. Three types of specimens were made, depending on the notch location, the specimen with a notch in basic metal (BM), weld metal (WM) and heat-affected zone (HAZ)

The experiments were conducted using the single-specimen method with successive partial unloading, i.e. the method of single-specimen relaxation. The aim of relaxation with unloading was to register the value of crack propagation, Δa, occurring during testing. The typical appearance of the diagrams $F - \delta$ and $J - \Delta a$ for the specimen with a notch in basic metal (BM) is given in Fig. 1 for room temperature, and Fig. 2, for operating temperature [7]. Computed values of plane-strain fracture toughness, K_{Ic}, are given in Tab. 3 for the specimens with notches in BM, WM and HAZ.

One can observe that structural and mechanical heterogeneities of a welded joint significantly affect its resistance to crack propagation, both in elastic and in plastic regions. Therefore, to issue test conditions of fracture mechanics, it is necessary to define not only the test procedure and location of a fatigue crack but the method of interpretation and meaning of the results as well [7].

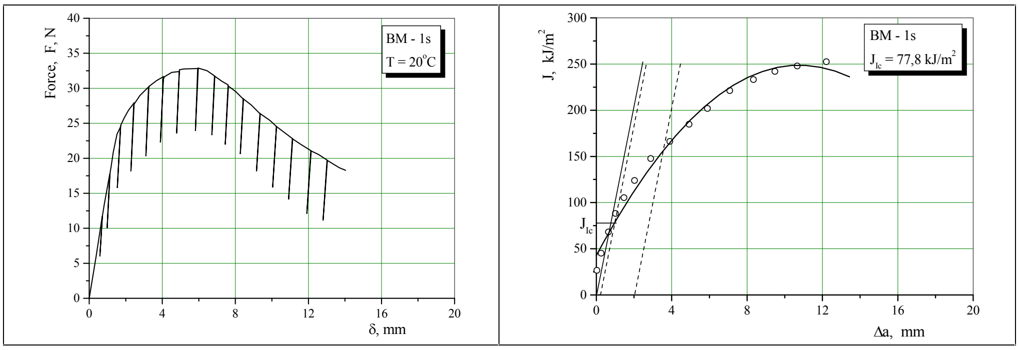

Figure 1: Diagrams F – δ and J – Δa for the specimen with a notch in BM for room temperature [7]

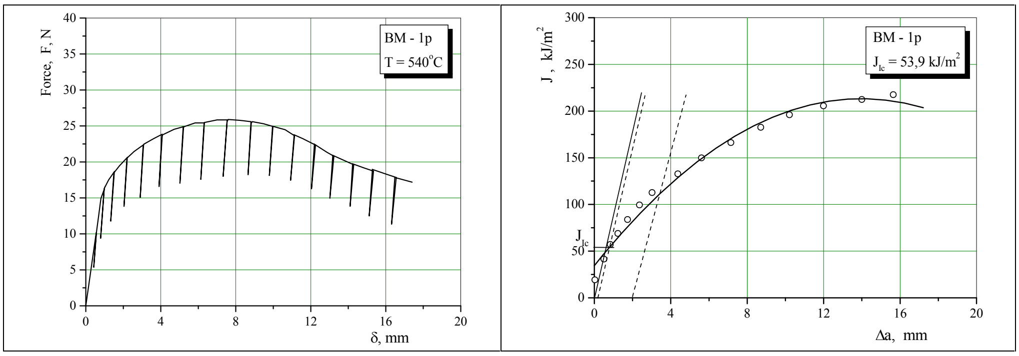

Figure 2: Diagrams F – δ and J – Δa for the specimen with a notch in BM for operating temperature [7]

Table 3: Results of testing the critical J-integral, J_{Ic}, and the critical stress intensity factor, K_{Ic} [7]

Sample mark	**Testing temperature, °C**	**Critical *J*-integral J_{Ic}, kJ/m^2**	**Critical stress intensity factor, K_{Ic}, MPa m$^{1/2}$**	**Critical crack length, a_c, mm**
BM-1s	20	77,8	132,4	52,8
BM-2s		80,5	134,7	54,7
BM-3s		73,2	128,4	49,7
WM-1s	20	82,2	136,1	55,8
WM -2s		93,7	145,3	63,6
WM -3s		97,2	148,0	66,0
HAZ-1s	20	65,1	121,1	44,2
HAZ -2s		80,2	134,4	54,5
HAZ -3s		78,3	132,8	53,2
BM-1p	540	53,9	90,2	46,1
BM-2p		49,7	87,4	43,4
BM-3p		55,1	92,1	48,1
WM -1p	540	62,2	97,8	54,3
WM -2p		60,3	96,3	52,6
WM -3p		55,6	92,5	48,5
HAZ -1p	540	48,7	86,6	42,5
HAZ -2p		53,9	91,1	47,0
HAZ -3p		50,7	88,3	44,2

The character of the curves varies depending on the location of a notch, i.e. on the point reached by a fatigue crack and test temperature. By analysing the curves obtained, one can observe identical dependence of the character of individual curves in each group, where the difference between the specimens lies exclusively in the value of maximum force, F_{max}, which is directly dependent on the length of a fatigue crack, a, and test temperature [5].

Heterogeneity of mechanical properties of a welded joint, i.e. the welded-joint components, is obvious from the obtained value of plane-strain fracture toughness, K_{Ic}, determined indirectly through critical J_{Ic} integral. The specimens with a notch in WM have the largest measured value of K_{Ic}. Average K_{Ic} values of ~143 MPa $m^{1/2}$ that were obtained are within the limits of the values in literature for this group of general structural steels. Somewhat lower K_{Ic} values were obtained for the specimens with a notch in BM, (mean value of K_{Ic} was ~132 MPa $m^{1/2}$). However, in this particular case the differences are relatively small, ranging from 10 to 15 MPa $m^{1/2}$ in terms of minimum and maximum value. The lowest values are that for HAZ, which anyway a critical spot in a welded joint is [7].

3.2 Application of fracture mechanics in study of fatigue.

Fatigue crack will initiate and propagate from severe stress raisers under variable loading after determined cycle 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 [8] 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. 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. During crack propagation, gauge foil breaks following the fatigue-crack tip. In that way, resistance of the gauge foil varies linearly with crack length variation.

Both fatigue-crack growth parameters at operating temperature of 540°C and fracture toughness were determined on CT specimens, whose geometry is defined by BS 7448 Part 1.

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 [9]. This relation can be calculated and drawn in a form log da/dN - log (ΔK), based on the results of tests conducted at room and operating temperature (540°C). Obtained relations are presented in Fig. 3 for the specimens pre-cracked in base metal (BM); weld metal (WM) and heat-affected-zone (HAZ) [7].

Obtained values of coefficient C and exponent m in the equation of Paris are given in Tab. 4, together with the values of stress-intensity factor range, ΔK_{th}, at fatigue threshold. The results presented in Tab. 6 clearly show that crack-tip position and testing temperature determine threshold stress-intensity factor range ΔK_{th} and fatigue-crack growth behaviour [7].

For comparison, the value of the stress-intensity factor range ΔK = 10 MPa√m is located in the portion of the curve where Paris law applies. Corresponding crack-growth rates at room temperature ranged from $1.24\cdot10^{-09}$ nm/cycle for base metal to $2.56\cdot10^{-09}$ nm/cycle for weld metal and $3.12\cdot10^{-09}$ nm/cycle in HAZ, indicating that HAZ is critical constituent in welded joint. At 540°C, crack-growth rates are significantly higher when compared to room temperature ($3.74\cdot10^{-09}$; $4.51\cdot10^{-09}$; 5.00 10^{-9} for base metal, weld metal and HAZ, respectively), but with smaller differences in constituents that can be explained by better ductility at elevated temperature. Again, HAZ is most critical constituent in welded joint [7].

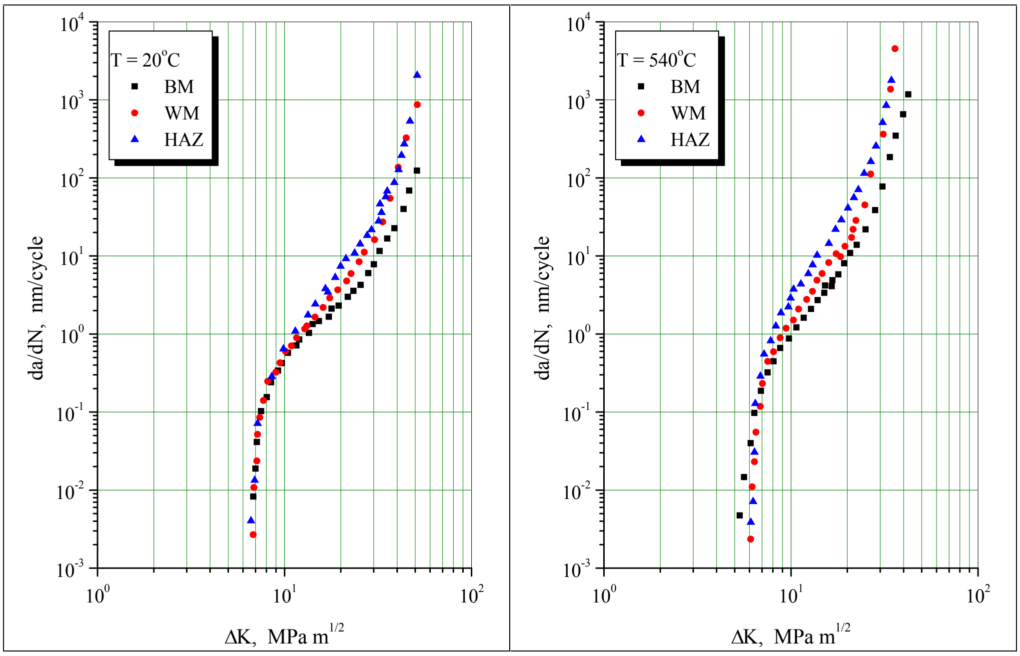

Figure 3: Fatigue-crack growth rate per cycle, da/dN, vs. stress-intensity factor range, ΔK, specimens pre cracked in BM, WM, and HAZ tested at room temperature (left) and at 540°C (right) [7]

Table 4: Parameters of Paris equations [7]

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, nm/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	$5.00 \cdot 10^{-09}$

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

The behaviour of welded joint as whole, as well as of their individual constituents, can be connected with the variation of the 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 base 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 [10].

4. CONCLUSIONS

Following conclusions can be derived:

- Structural and mechanical heterogeneities of a welded joint significantly affect the resistance to crack propagation, both in elastic and in plastic region. The heterogeneity of the mechanical properties of the welded joints, i.e. welded-joint components, is obvious from the values obtained for plane-strain fracture toughness, K_{Ic}, determined indirectly through the critical J_{Ic} integral.
- Decisive effect on stress-intensity factor range ΔK and fatigue-crack growth parameters can be attributed to the location of machined notch and following initial crack, as well as to testing temperature.
- The highest resistance to crack propagation, expressed by minimum fatigue-crack growth rate, exhibited the specimens pre-cracked in basic metal, and maximum fatigue crack-growth rate was found in the 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 behaviour of pre-cracked specimens taken from different welded joint constituents (basic metal, weld metal, heat-affected-zone), tested at operating temperature (540°C) and under variable loading, regarding fatigue threshold and fatigue crack growth parameters, exhibited two to four-fold higher crack-growth rate when compared to room temperature, which can be explained by reduced properties at elevated temperature.

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