UDK: 772.96:539.42:621.74.047
COSATI: 11-06, 13-05, 20-12

Effect of Structural Heterogeneity on the Fracture Mechanics Parameters of Welded Joints of A.387 Steel

Meri Burzić[1)]
Radica Prokić-Cvetković[2)]
Olivera Popović[2)]
Zijah Burzić[3)]

For better understanding of the phenomenon of crack initiation and propagation in welded joints of A-387 Gr. 11 steel designed for high-temperature and high-pressure applications, it is necessary to determine the effect of the heterogeneity of microstructural and mechanical properties on fracture toughness and fatigue crack initiation and propagation. Based on the tests conducted with pre-cracked CT and Charpy size specimens, the effect of the heterogeneity of the microstructural and mechanical properties of welded joints on fracture toughness and fatigue-crack growth parameters was determined.

Key words: **alloy steel a-387 Gr. 11 class 1, welded joint, fracture toughness, Paris law, fatigue crack growth rate.**

Introduction

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

The welding technology specification of A-387 Gr. 11 Class 1 steel plates, 96mm thick, is defined according to standard ISO 15614-1 [2]. However, this standard requires neither testing of operating temperature (540°C) nor testing of the in-service behaviour of a base metal and a welded joint at room and operating temperatures.

The problem of determination of fracture toughness, K_{Ic}, is treated as a problem of principle, as fracture mechanics assumes homogeneous material not only near the crack tip but at some distance from it as well, in order to make theoretical assumptions and meanings of fracture toughness as a property measured using some of the methods of fracture mechanics still valid. A 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 an 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, a great interest in the application of the investigations of fracture mechanics in the case of welded joints is natural [3,4].

For a better understanding of the cause and the 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 the heterogeneity of microstructure and mechanical properties on fracture toughness, K_{Ic}, and the 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 [5].

Material

For the assessment of the effect of operating temperature on fracture toughness, K_{Ic}, and the fatigue-crack growth parameters of A-387 Gr. 11 Class 1 steel, a sample of 350 x 500 x 96mm with double U weld metal in the centre was available.The spesimens for the qualification of the welded joint, the WM and the HAZ were machined from a welded sample plate. [6]. The chemical composition and the mechanical properties of A-387 Gr. 11 Class 1 steel are shown in Tables 1 and 2, respectively.

Table 1. Chemical composition of the tested material

Chemical composition, mass %						
C	Si	Mn	P	S	Cr	Mo
0.15	0.29	0.54	0.022	0.011	0.93	0.47

Table 2. Mechanical properties of the tested material [6]

Yield stress $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation A, %	Impact energy, J
325	495	35	165

1) University of Belgrade, Faculty of Mechanical Engineering, IC, Kraljice Marije 16, 11020 Belgrade 35, SERBIA
2) University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11020 Belgrade 35, SERBIA
3) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

The plates were welded by two procedures [6]:

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

The chemical compositions of the coated electrode LINCOLN Sl 19G and the wire LINCOLN LNS 150 according to certificates are given in Table 3. The main mechanical properties according to certificates are given in Table 4.

Results and discussion

Fracture toughness, K_{Ic}.

The effect of the heterogeneity of the structure and the mechanical properties of a welded joint reflects in the location of a fatigue-crack tip in the first place, and in the properties of the region where a fracture develops. Testing of the plane-strain fracture toughness of the specimens taken from a welded plate made of A-387 Gr. 11 Class 1 steel was conducted. The aim was to determine the critical stress-intensity factor, K_{Ic}, i.e. to estimate the behaviour of base metal (BM) and the components of the welded joint, weld metal (WM) and the heat-affected zone (HAZ) in the 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, the geometry of which is defined by the BS 7448-Part 1 standard [7]. Three-point bend (TPB) specimens were used for testing at room temperature. Due to a specific design of the chamber, CT specimens were used for testing at an operating temperature of 540°C. Three types of specimens were made, depending on the notch location:

- 1st - the specimen with a notch in the base metal (BM)
- 2nd - the specimen with a notch in the weld metal (WM)
- 3rd - the specimen with a notch in the 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.

Based on the data collected from the tearing machine and the COD indicator, the diagrams force, F, and the crack mouth opening displacement (CMOD), δ, were plotted, serving as a foundation for plotting the diagram J – Δa, where the regressive line is plotted according to ASTM 1152-02 [8]. The critical J-integral, J_{Ic}, is obtained from the regressive line obtained. The typical appearance of the diagrams $F-\delta$ and $J-\Delta a$ for the specimen with a notch in the base metal (BM) is given for room temperature in Fig.1 and in Fig.2 for operating temperature. From the very appearance of the diagrams, the effect of structural heterogeneity on the toughness of the parent metal and the welded-joint components is obvious [9].

The value of the critical stress-intensity factor or plane-strain fracture toughness, K_{Ic}, can be computed when the values of the critical J_{Ic} integral are known, using the dependences

$$K_{Ic} = \sqrt{\frac{J_{Ic} \cdot E}{1-\nu^2}} \qquad (1)$$

The computed values of plane-strain fracture toughness, K_{Ic}, are given in Table 5 for the specimens with notches in the BM, the WM and the HAZ.

One can observe that the 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 the location of a fatigue crack but the method of interpretation and meaning of the results as well [9].

Table 3. Chemical composition of the filler metal [6]

Filler metal	Chemical composition, mass %						
	C	Si	Mn	P	S	Cr	Mo
LINCOLN Sl 19G	0.08	0.045	0.35	0.025	0.025	1.10	0.50
LINCOLN LNS 150	0.11	0.18	0.37	0.020	0.020	1.04	0.47

Table 4. Mechanical properties of the filler metal [6]

Filler metal	Yield stress $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation, A, %	Impact energy, J
LINCOLN Sl 19G	505	640	23	> 95
LINCOLN LNS 150	490	610	26	> 100

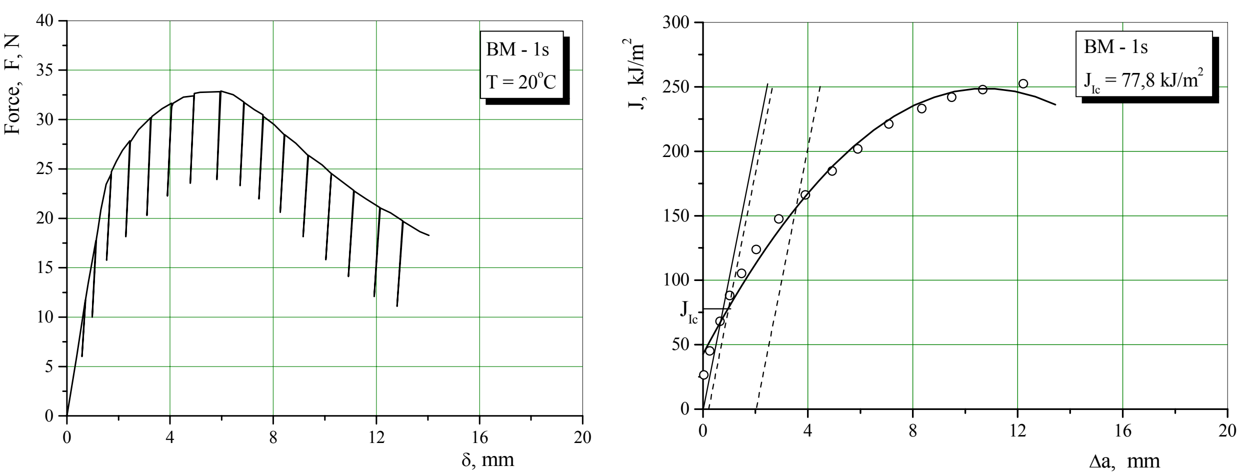

Figure 1. Diagrams $F-\delta$ and $J-\Delta a$ for the specimen with a notch in BM for room temperature [9]

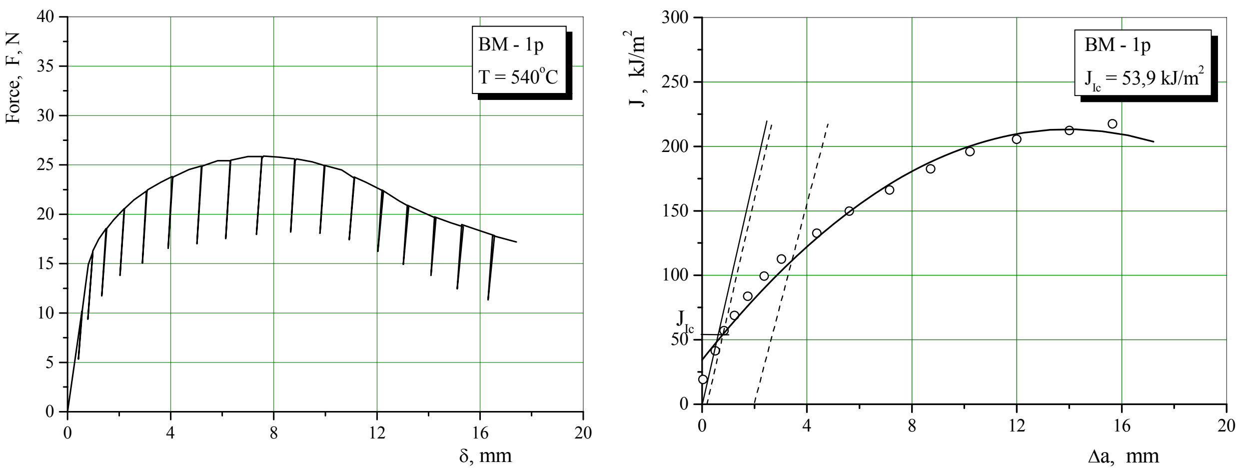

Figure 2. Diagrams $F - \delta$ and $J - \Delta a$ for the specimen with a notch in BM for operating temperature [9]

Table 5. Results of testing the critical *J*-integral, J_{Ic}, and the critical stress intensity factor, K_{Ic} [9]

Sample mark	Testing temperature, °C	Critical *J*-integral J_{Ic}, kJ/m²	Critical stress intensity factor, K_{Ic}, MPa m$^{1/2}$	Critical crack length, a_c, mm
BM-1s		77.8	132.4	52.8
BM-2s	20	80.5	134.7	54.7
BM-3s		73.2	128.4	49.7
WM-1s		82.2	136.1	55.8
WM -2s	20	93.7	145.3	63.6
WM -3s		97.2	148.0	66.0
HAZ-1s		65.1	121.1	44.2
HAZ -2s	20	80.2	134.4	54.5
HAZ -3s		78.3	132.8	53.2
BM-1p		53.9	90.2	46.1
BM-2p	540	49.7	87.4	43.4
BM-3p		55.1	92.1	48.1
WM -1p		62.2	97.8	54.3
WM -2p	540	60.3	96.3	52.6
WM -3p		55.6	92.5	48.5
HAZ -1p		48.7	86.6	42.5
HAZ -2p	540	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 the test temperature. By analysing the curves obtained, one can observe an identical dependence of the character of individual curves in each group, where the difference between the specimens lies exclusively in the value of the maximum force, F_{max}, which is directly dependent on the length of a fatigue crack, a, and the test temperature [6].

The heterogeneity of the 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 the critical J_{Ic} integral. The specimens with a notch in WM have the largest measured value of K_{Ic}. The average K_{Ic} values of ~143MPa m$^{1/2}$ that were obtained are within the limits of the values in literature for this group of general structural steels [5]. Somewhat lower K_{Ic} values were obtained for the specimens with a notch in BM, (mean value of K_{Ic} was ~132MPa m$^{1/2}$). However, in this particular case, the differences are relatively small, ranging from 10 to 15MPa m$^{1/2}$ in terms of the minimum and maximum value. The lowest values are that for the HAZ, which is a critical spot in a welded joint [9].

However, much more important is the effect of temperature on the values of fracture toughness, K_{Ic}. At operating temperature, the average reduction of fracture toughness is 35-45%, depending on the location of a fatigue-crack tip (BM, WM or HAZ). A tendency to brittle fracture at operating temperature is much more prominent, which requires more a frequent NDT control.

These differences do not necessarily affect significantly the structures exposed to static loading in service. However, under conditions where the structural components are permanently exposed to variable loading, the variations in the K_{Ic} values are very important, as the critical crack length, a_c, i.e. resistance to crack propagation, directly depends on the K_{Ic} value. By applying the fundamental formula of fracture mechanics

$$K_{Ic} = \sigma \cdot \sqrt{\pi \cdot a_c} \qquad (2)$$

and introducing the value of allowable stress $\sigma_{doz} = \sigma$, assuming that the shape factor equals to one, the approximate values of the critical crack length, a_{cr}, can be computed.

Having in mind that the thickness of the BM and the welded joint is 96 mm, in our opinion, in spite of an increasing tendency to brittle fracture at operating temperatures, the values obtained for critical crack length, a_c, are significant data for the prevention of possible undesirable consequences through prompt detection. Therefore, in order to ensure detection of cracks before they reach their critical length, proper procedures of non-destructive testing should be applied.

Application of fracture mechanics in a study of fatigue.

A fatigue crack will initiate and propagate from severe stress raisers under variable loading after a determined cycle number if the stress-intensity factor range, ΔK_{th}, for the fatigue threshold is achieved. The structure can be used before a growing crack reaches a critical value, based on a performed structural integrity analysis. Substantial data for the decision about an extended service of a cracked component is the crack growth rate and its dependence on the acting load. ASTM E647 standard [7] defines the testing of a pre-cracked specimen for the fatigue crack growth rate measurement da/dN, and the calculation of the stress intensity factor range, ΔK. Two basic requirements in ASTM E647 standard are a crack growth rate above 10^{-8} m/cycle to avoid the threshold ΔK_{th} regime, and testing with constant amplitude loading.

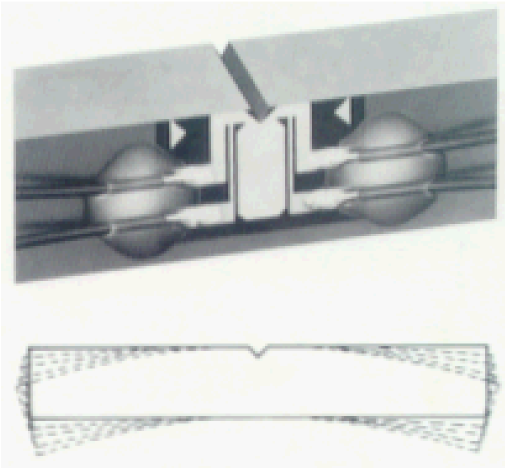

Figure 3. View of a specimen with a cemented-foil crack gauge-foil with a variable loading bending scheme

Standard Charpy size specimens, pre-cracked in different welded joint regions, were tested under variable loading for the determination of a stress-intensity factor range at the fatigue threshold, ΔK_{th}, and the fatigue crack growth rate da/dN. Testing was performed in load control, by three-points bending on a high-frequency resonant pulsator CRACKTRONIC, Fig.3.

This FRACTOMAT device is based on electrical potential measurement, connected with corresponding instruments. For monitoring the 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, the gauge foil breaks following the fatigue-crack tip. In that way, the resistance of the gauge foil varies linearly with a crack length variation.

Both fatigue-crack growth parameters at the 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 the exponent m in the equation of Paris [11]. This relation can be calculated and drawn in a form log da/dN - log (ΔK), based on the results of the tests conducted at room and operating temperature (540°C). The obtained relations are presented in Fig.4 for the specimens pre-cracked in base metal (BM); weld metal (WM) and the heat-affected-zone (HAZ) [9].

The obtained values of the coefficient C and the exponent m in the equation of Paris are given in Table 6, together with the values of the stress-intensity factor range, ΔK_{th}, at the fatigue threshold. The results presented in Table 6 clearly show that the crack-tip position and testing temperature determine the threshold stress-intensity factor range ΔK_{th} and the fatigue-crack growth behaviour [9].

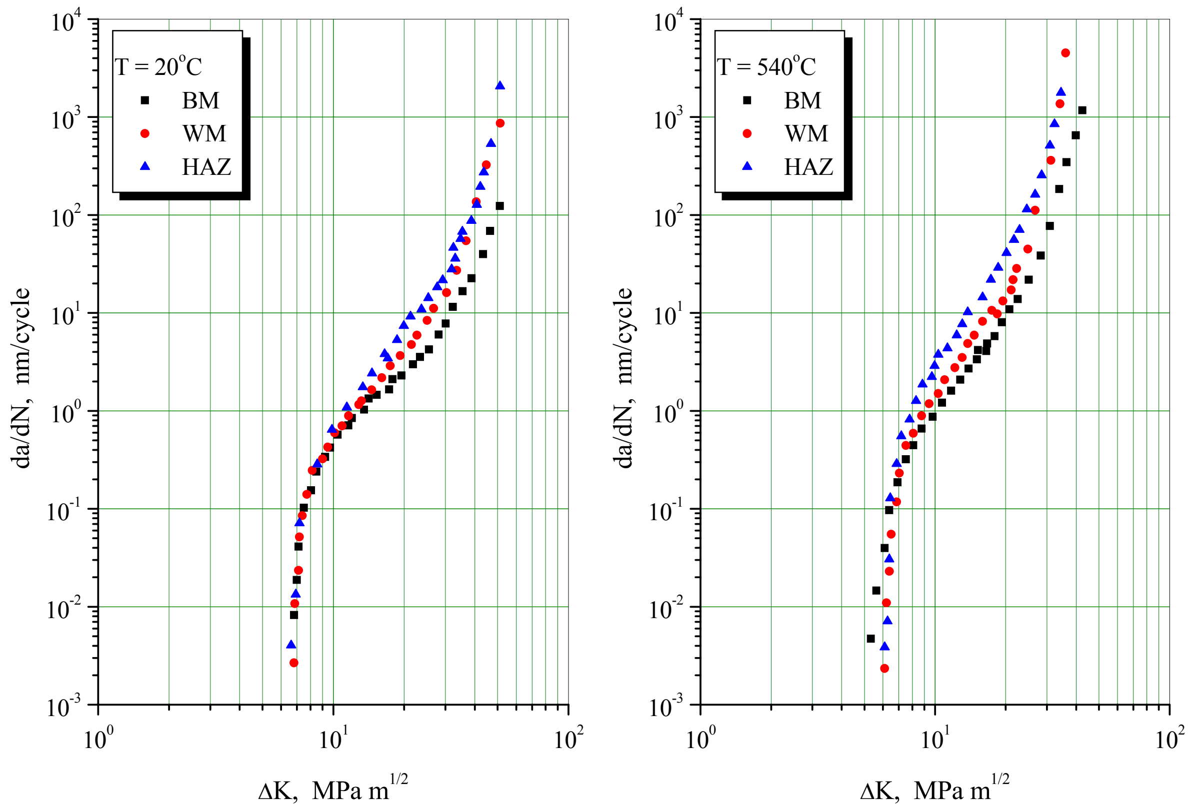

Figure 4. Fatigue-crack growth rate per cycle, da/dN, vs. The stress-intensity factor range, ΔK, specimens pre cracked in BM, WM, and the HAZ tested at room temperature (left) and at 540°C (right) [9]

Table 6. Parameters of Paris equations [9]

Specimen designation	Test temperature, °C	Stress-intensity factor range at the fatigue threshold, ΔK_{th}, MPa m$^{1/2}$	Coefficient C	Exponent m	Crack-growth rate da/dN, nm/cycle at ΔK = 10MPa m$^{1/2}$
BM–1s		6.8	$2.98 \cdot 10^{-13}$	3.62	$1.24 \cdot 10^{-9}$
WM–1s	20	6.8	$3.88 \cdot 10^{-13}$	3.82	$2.56 \cdot 10^{-9}$
HAZ–1s		6.7	$3.05 \cdot 10^{-13}$	4.01	$3.12 \cdot 10^{-9}$
BM–1p		5.9	$3.11 \cdot 10^{-13}$	4.08	$3.74 \cdot 10^{-9}$
WM–1p	540	6.2	$3.27 \cdot 10^{-13}$	4.14	$4.51 \cdot 10^{-9}$
HAZ–1p		6.1	$3.38 \cdot 10^{-12}$	3.17	$5.00 \cdot 10^{-9}$

For comparison, the value of the stress-intensity factor range ΔK = 10MPa√m is located in the portion of the curve where Paris law applies, as shown in Fig.4. Corresponding crack-growth rates at room temperature ranged from $1.24 \cdot 10^{-9}$ nm/cycle for base metal to $2.56 \cdot 10^{-9}$ nm/cycle for weld metal and $3.12 \cdot 10^{-9}$ nm/cycle in the HAZ, indicating that the HAZ is a critical constituent in a welded joint. At 540°C, crack-growth rates are significantly higher when compared to room temperature ($3.74 \cdot 10^{-9}$; $4.51 \cdot 10^{-9}$; $5.00\ 10^{-9}$ for base metal, weld metal and the HAZ, respectively), but with smaller differences in constituents that can be explained by better ductility at elevated temperature. Again, the HAZ is the most critical constituent in a welded joint [9].

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

The behaviour of a welded joint as whole, as well as of its individual constituents, can be connected with the variation of the slope of the valid portion of the Paris curve. In general, materials with lower fatigue-crack growth are characterized by a lower slope on the diagram da/dN vs. ΔK. Lower crack propagation is confirmed on specimens from base metal and from weld metal, requiring a higher stress-intensity factor range for the same crack growth rate. The maximum fatigue-crack growth rate can be expected at the level of the stress-intensity factor approaching to plane-strain fracture toughness - the condition for brittle fracture [12].

Conclusions

The following conclusions can be derived:

- Structural and mechanical heterogeneities of a welded joint significantly affect the resistance to crack propagation, both in the elastic region and in the plastic region. The heterogeneity of the mechanical properties of welded joints, i.e. welded-joint components, is obvious from the values obtained for the plane-strain fracture toughness, K_{Ic}, determined indirectly through the critical J_{Ic} integral.
- A decisive effect on the stress-intensity factor range ΔK and the fatigue-crack growth parameters can be attributed to the location of a machined notch and the following initial crack, as well as to testing temperature.
- The highest resistance to crack propagation, expressed by the minimum fatigue-crack growth rate, exhibited the specimens pre-cracked in base metal, and the maximum fatigue crack-growth rate was found in the specimens pre-cracked in the heat-affected-zone. This is directly connected with the effect of the microstructural heterogeneity of welded-joint constituents on the fatigue-crack growth rate da/dN.
- The behaviour of the pre-cracked specimens taken from different welded joint constituents (base metal, weld metal, heat-affected-zone), tested at operating temperature (540°C) and under variable loading, regarding the fatigue threshold and the fatigue crack growth parameters, exhibited a 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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Received: 12.11.2014.

Uticaj heterogenosti strukture na parametre mehanike loma zavarenog spoja čelika A387

Radi potpunijeg razumevanja uzroka i načina pojave i rasta prslina u zavarenim spojevima čelika A-387 Gr.11 predviđenog za rad u uslovima povišene temperature i pritiska, potrebno je da se utvrdi kako heterogenost strukture i mehaničkih svojstava zavarenog spoja, utiče na žilavost loma i pojavu i rast zamorne prsline. Ispitivanjem CT i Šarpi epruveta sa iniciranom zamornom prslinom data je ocena kako heterogenost strukture i mehaničkih svojstava zavarenog spoja utiču na parametre žilavosti loma i brzinu rasta zamorne prsline.

Ključne reči:: **legirani čelik A387 Gr. 11 Class 1, zavareni spoj, žilavost loma, Parisov zakon, rast zamorne prsline.**

Влияние структурной неоднородности на параметры механики разрушения сварного соединения стали A387

Для более полного понимания причин и способов инициирования и роста трещин в сварных соединениях стали A-387 Gr.11, запланированной к работе в условиях повышенной температуры и давления, необходимо установить неоднородную структуру и механические свойства сварных соединений и их влияние на вязкость разрушения и появление и рост усталостных трещин. Рассматривая КТ и Шарпи-образцы с инициированной усталостной трещиной определена и дана оценка как гетерогенная структура и механические свойства сварных швов влияют на параметры вязкости разрушения и скорость роста усталостной трещины.

Ключевые слова: **легированная сталь A387 Gr. 11 класс 1, сварной шов, прочность на разрыв, закон Париса, рост усталостных трещин.**

Effet de l'hétérogénéité structurale sur les paramètres de la mécanique de fracture chez le joint soudé de l'acier A387

Pour mieux comprendre le phénomène de la cause et de la façon de l'apparition et de la croissance des fractures chez les joints soudés de l'acier A-387 Gr.11 conçu pour l'utilisation dans les conditions de la température et de la pression élevées il est nécessaire de déterminer comment l'hétérogénéité structurale ainsi que des propriétés mécaniques du joint soudé influencent sur la résistance de fracture et sur l'apparition et la croissance de la fatigue de fracture . En examinant les éprouvettes CT et Charpy avec la fracture de fatigue provoquée on a déterminé comment l'hétérogénéité structurale et des propriétés mécaniques du joint soudé influençaient sur les paramètres de la résistance de fracture ainsi que sur la vitesse de croissance chez la fracture de fatigue.

Mots clés: **acier allié, joint soudé, résistance de fracture, loi de Paris, croissance de la fracture de fatigue.**