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Original article

Determining of the Fatigue Crack Growth Rate of HSLA Steel at Room Temperature

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ABSTRACT

Welded joint is a critical region of a welded structure and fracture mechanics analysis is inevitable in the structural integrity assessment of all welded structures. This paper shows the determining of parameters of the fatigue crack for constituents of welded joints produced of high strength low alloyed steel. The applied methodology refers to the Paris relation where the link was established between the variable load quantity or the corresponding stress intensity factor range and crack growth per cycle. Results have shown that the position of the notch and crack initiation affect the values of the stress intensity range of fatigue threshold ΔK_{th} and parameters in the Paris' equation. This is mostly expressed when determining growth parameters of the fatigue crack in heat affected zone of HSLA steel, where different changes of growth speed of the fatigue crack clearly express differences in structure of the crack pass.

Key words: *crack growth rate, welded joint, HSLA steel, welded joint;*

1. INTRODUCTION

To produce safe pressure equipment like hydraulic and gas cylinders, pressure vessels and pipelines, weldable high strength low alloyed (HSLA) steels have been applied. In most components of welded objects, defects in welded joints as sub-critical cracks are present, caused during manufacturing, or being induced in shipping or assembling. However, catastrophic failures of welded structures still occur, due to development of cracks or defects contained in material or introduced during proof testing and operation. Some cracks can be initiated and propagated under service loading and environment effect until a particular crack reaches the size critical for failure. In order to prevent failure, it is necessary to know the conditions under which the subcritical crack growth occurs, their initial sizes and their behaviour in service. From safety and economics reason it is crucial to avoid the failure [1].

The development of cracks during fatigue loading on smooth and homogeneous designed shapes due to local stress concentration in design geometry of the welded structure and at cross-section changes still cannot be explained by simple relations between strain, stress, fatigue characteristics, and cross-section area size, and empirically derived dependencies are used, generally requiring additional experimental testing [2].

The parallel introduction of experimental and theoretical approaches has enabled the development of studying the behavior of materials under variable loading because only a theoretical approach cannot fully explain crack growth rate [3]. Basically, fracture mechanics relates crack length, stress intensity, and resistance material expressed by stress intensity factor or can be estimated crack growth

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rate in the form of crack increment per cycle. As proof of the above, on diagram in Fig. 1. it can be seen that the crack grows at higher stress and that at the same time fracture occurs with fewer cycles. It can be stated that the total life to fracture depends on the existence of the initial crack in the material, stress and resistance of the material according to fracture [4].

An opening or groove, depending on the method of testing, is being machined on the specimen in order to cause the initiation of the crack on desired location. After crack initiation, crack length is measured, *a*, depending on the number of cycles, *N*, and the crack growth rate is calculated, *da/dN*, which depends on the stress amplitude and current crack length.

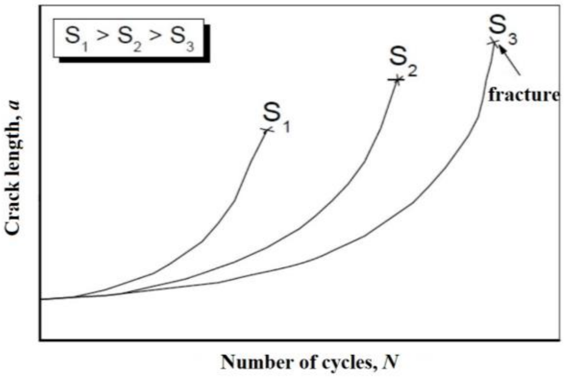

Fig. 1 *Typical dependence between number of cycles and crack length*

2. FATIGUE CRACK GROWTH RATE

Paris, Gomez and Anderson have first proposed in 1961 that the crack growth rate, *da/dN*, might be correlated with the stress intensity factor range, ΔK, when the material is exposed to variable loading of constant amplitude [5]. This approach has been adopted for the characterisation of fatigue crack growth in the condition of small-scale plastic deformation at the crack tip.

Under variable loads, the crack can initiate from an existing defect or damage at maximum values of stress, well below quasi-static fracture toughness. In the small-scale yielding condition, when the non-linear zone in fact represents a disturbance in the otherwise elastic material, Paris, Gomez and Anderson (1961), and later Paris and Erdogan (1963) had supposed that the crack growth under variable loads would follow the law, usually known as the Paris' law [6]:

$$\frac{da}{dN} = C \cdot \Delta K^{m} \tag{1}$$

where is ΔK is stress intensity factor range presented as a difference between maximum and minimum stress intensity factors corresponding to the maximal and minimal load in a cycle. C and m are constants depending of material properties.

It is important to point out that the Paris crack growth relation is not valid in the whole area. Paris relation is between low speeds near the fatigue threshold (ΔK_{th}) and high speeds (ΔK_{Ic})-regime II. Fig. 2 shows three different regimes of crack growth:

- regime I - low speed of propagation
- regime II – stable propagation
- regime III - high speed of propagation to the fracture

In Fig. 2 central portion of the crack growth curve is linear in the log-log scale. This relation is from a practical point of view proved to be by far the most important because at the same time it allows a distinction to be made between fatigue crack initiation and fatigue crack growth, see Fig. 2.

The application of the Paris relation proved to be particularly applicable in the field of fatigue construction made of high-strength materials, which is the case in this paper on example of HSLA steel [4].

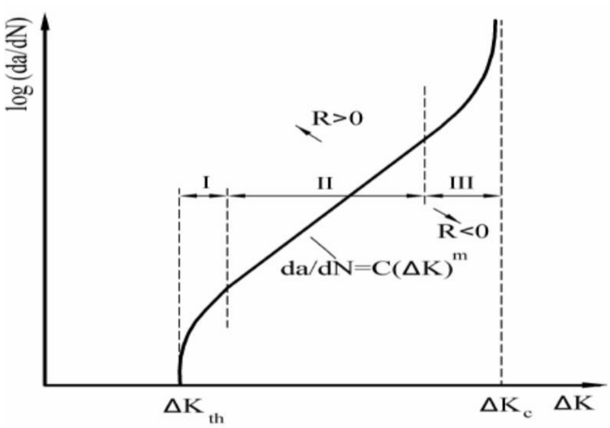

Fig. 2 *Typical plot of crack growth rate with respect to the stress intensity range where the Paris equation fits the central, linear region of Regime II*

3. EXPERIMENTAL PROCEDURE

The material used in the current experimental study was welded joint of high strength low-alloy steel (HSLA) Nionikral-70 (NN-70), Yugoslav version of American steel HY-100, designed for ship structures and pressure vessels [7]. The technology of manufacture and thermomechanical processing, of Nionikral-70 steel is the result of joint research from the Military Technical Institute in Žarkovo (VTI) and ironworks Jesenice from Jesenice (Slovenia), in the early 1990s.

High strength is achieved by combining classical quenching and tempering, and additional grain refining by an optimal combination of chemistry, microalloying and corresponding precipitation. Care is devoted to obtain the best combination of strength, ductility, toughness, crack resistance to initiation and growth, and the stability of these properties at low temperatures, high resistance to fatigue and stress corrosion, and in any case–good workability and weldability [8]. The chemical composition of NN-70 is given in Table 1 and its mechanical properties are given in Table 2.

Table 1 *Chemical composition of NN-70 (% wt)*

C	Si	Mn	P	S	Cr	Ni
0.106	0.209	0.220	0.005	0.017	1.258	2.361

Table 2 *Mechanical properties of NN-70*

Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
645	914	22.4

The specimens used in this testing are standard Charpy specimens of rectangular cross-section, with the ground and polished faces, taken from shielded manual arc butt welded 20 mm thick plates (preheat temperature 170 °C, current: Ø2.5mm-95 A and Ø3.25 mm-116 A). The properties of weld metal largely depend on the selection of an adequate electrode, in this case for filling the K groove. Therefore, the Charpy specimens are made of parts of the plates NN-70 welded by the overmatching effect using the EVB 75 electrode from the company "Elektrode Jesenice" from Slovenia. EVB 75 is an alloyed basic electrode for welding fine-grained steels and HSLA steels. Dimensions of specimens are L=55 mm, W=10 mm, B=10 mm and 2 mm deep notch, see Fig. 3.
Using high frequency resonant testing machine Rumul Cracktronic pulsator 160 Nm (Rumul-Russenberger Prüfmaschinen AG, Neuhausen am Rheinfall, Switzerland) determining the fatigue crack growth rate *da/dN* and fatigue threshold ΔK_{th} are performed with specimens from parent metal, weld metal, and heat-affected-zone of HSLA welded joint, at room temperature. Crack growth is monitored by measuring potential drop by strain gauge Rumul RMF A-5 (Rumul-Russenberger Prüfmaschinen AG, Neuhausen am Rheinfall, Switzerland), measuring 5 mm length, located on the specimen face surface. Strain gauges Rumul RMF A-5 of 5 mm length are cemented on machined specimens, allowing crack growth monitoring by Fractomat (Rumul-Russenberger Prüfmaschinen AG, Neuhausen am Rheinfall, Switzerland) crack length measuring device, based on the electrical potential of gauge and connected with instrumentation [9].
The standard ASTM E647 is used for determining the stress intensity factor range [10]. In fact, the relationship between the fatigue crack growth rate per cycle *da/dN* and the range of stress intensity factor ΔK is reduced to determine the coefficient C and the exponent m in the Paris equation. Stress intensity factor range ΔK, which depends on the geometry of the specimen, the length of the crack, and on the range of variable force, should be added to the fatigue crack growth rate for current crack length a [11]. Fatigue crack growth rate is determined based on obtained relationships of crack length a–number of cycles N. Obtained dependence curves a–N is used as the basis for determining fatigue crack growth rate, *da/dN*.

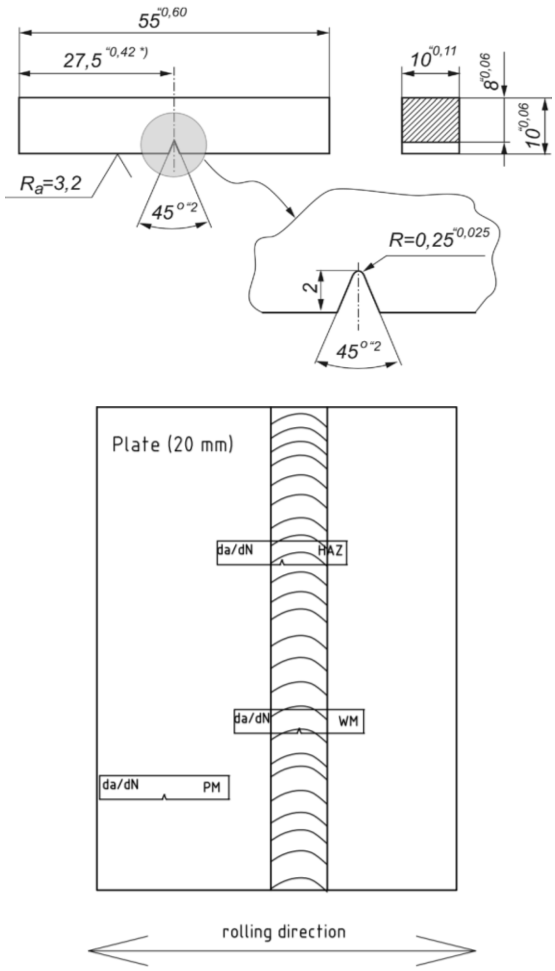

Fig. 3 *Plate with position of specimens and dimensions of Charpy specimen*

4. RESULTS AND DISCUSSION

The diagrams *log(da/dN)* vs. *log*ΔK with results of the fatigue threshold ΔK_{th} and material parameters-coefficient C and exponent m for fatigue crack growth for parent metal (PM), weld metal (WM) and heat-affected-zone (HAZ) are presented in in Fig. 4 to 6, respectively.

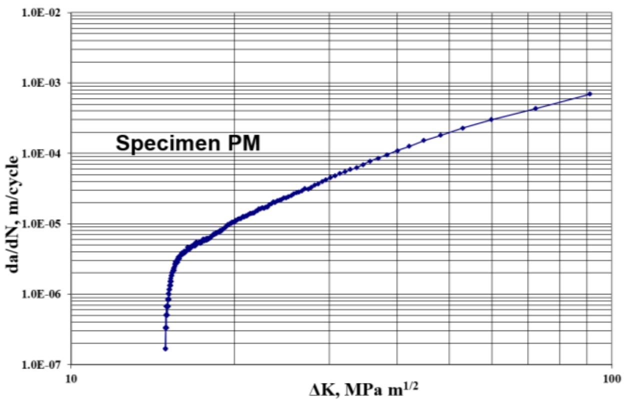

Fig. 4 *Crack growth rate vs. stress intensity factor range for PM (ΔK_{th}=14.93 MPa·m$^{1/2}$, C=3.74·10^{-10}, m=3.43)*

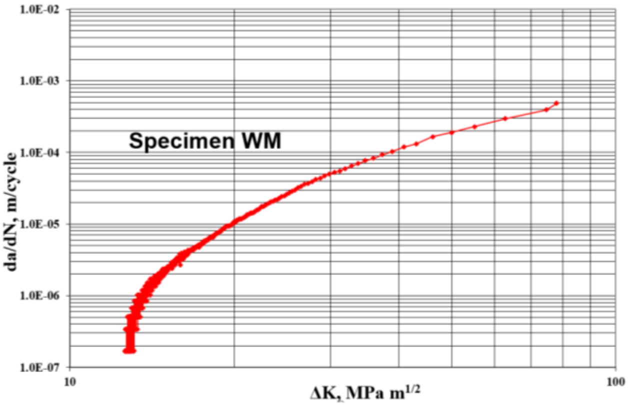

Fig. 5 *Crack growth rate vs. stress intensity factor range for WM (ΔK_{th}=12.85 MPa·m$^{1/2}$, C=1.53·10^{-11}, m=4.47)*

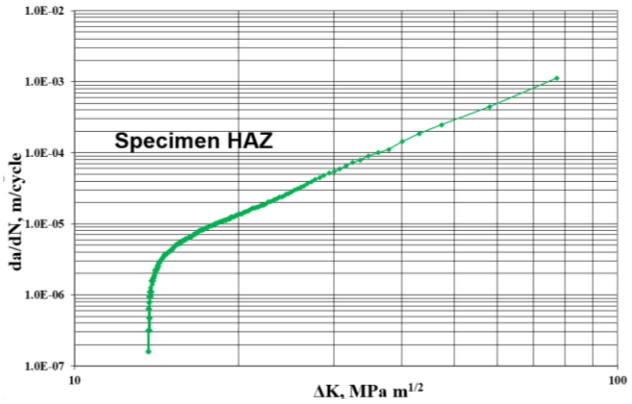

Fig. 6 *Crack growth rate vs. stress intensity factor range for HAZ (ΔK_{th}=13.70 MPa·m$^{1/2}$, C=5.90·10^{-10}, m=3.35)*

5. CONCLUSIONS

Observing the values from the diagrams in Fig. 4 to 6, fatigue threshold ΔKt_h obtained for parent metal are higher than corresponding test values for specimens notched in weld metal and heat-affected-zone. Lowest fatigue crack growth (highest crack propagation resistance) has parent metal then weld metal while the lowest crack propagation resistance has a sample with the crack in heat-affected-zone, in the region of Paris law validity. Specimen with the crack in the heat-affected zone has the worst crack propagation resistance. Analyzing the obtained results it can be concluded that the welded joint of high strength low-alloy steel geometrically imperfect shape especially observed in the determination fatigue crack growth rates of welded joint NN-70.

The results show that the position of the notch and crack initiation have an impact on fatigue threshold values ΔKt_h and parameters of the Paris equation, which is special expressed when determining fatigue growth parameters near the heat affected zone of welded joint NN-70, where different changes fatigue crack growth rates clearly indicate different crack pass structures.

Based on the above Paris equation is suitable for the fatigue of structures made of high-strength materials, especially HSLA steel. The behavior of the welded joint has shown that fatigue properties are not significantly reduced by welding, but for a better understanding of the fatigue crack behavior in individual constituents of welded joints, a further investigation is necessary.

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