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Application of Paris' Law Under Variable Loading

The most important characteristics for service safety of welded joints are those describing crack initiation and growth caused by variable loading. Crack initiation and growth caused by variable loading is the subject of numerous investigations. This paper shows the determination of parameters of the fatigue crack for constituents of welded joints produced of high strength low alloyed steel. The crack growth law of Paris establishes the relation between the applied 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.

Keywords: *Paris' law, crack growth rate, welded joint*

1. INTRODUCTION

Safety and reliability in operating conditions are the main requirements each welded structure has to satisfy. The characteristics of welded joints have a significant impact to fulfil this requirement. A detailed description of welded joint properties requires experimental investigations and interpretation of obtained results since complex structures are in question [1].

The integrity of welded joints test has to consider the influence of the fatigue crack and its threshold value, eventually followed by in-service propagation through parent metal (PM), weld metal (WM), and heat-affected-zone (HAZ) of the welded joint. Since a detected crack can initiate after a certain time, the corresponding data have to be defined in the material specification [2].

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 [1].

Surface cracks, caused by imperfections in the welded joint, such as inclusions, overheating, corrosion damages, cracks in the fusion region, welder's markings are the most frequent defects in welded structures. Propagation of surface crack in the typical plot of crack growth rate presents a crucial problem, asking to consider also the cases after its initiation [3].

Paris, Gomey, 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. However, the leading journals in this area did not accept publishing the offered paper, considering that this approach has certain shortcomings. This approach has been adopted for the characterization of fatigue crack growth in the condition of small-scale plastic deformation at the crack tip. Linear elastic fracture mechanics (LEFM) has postulated that the stress intensity factor range, determined according to remote stress and the cracked component geometry unambiguously characterize fatigue crack growth, even when the fatigue fracture mechanism is not known [3].

To understand as much as possible the causes and modes of crack occurrence and growth in welded joints of high strength steels, it is necessary to determine how the heterogeneity of microstructure and mechanical properties of welded joints, primarily of HAZ, affect crack initiation and growth, as well as fatigue crack growth parameters.

Fracture mechanics has defined parameters and introduced new test methods, to better determine the tendency to crack growth, critical conditions for rapid fracture development, material resistance to rapid crack propagation, or in other words to assess material behavior and structural integrity in the presence of cracks.

The integrity of welded joints under the impact of variable loading is the dominant topic of all serious researchers in this field of testing nowadays, so that part of the research within this topic is focused on analyzing the impact of variable loading on the behavior of welded steel Nionikral-70 (HSLA steel), in the presence of cracks, respectively the determination of fatigue crack growth parameters.

The safety of brittle fracture joints, which, when it comes to welded structures with a small exception of ultra-high-strength materials, belongs to the field of elastic-plastic fracture mechanics, encounters many unsolved problems, some of which are of a fundamental nature. The source of all the problems is in the fact that the potentially weak and dangerous place of low fracture toughness is not the joint as a whole, but a very narrow area most often localized in the critical part of the heat-affected zone, or weld metal. This is very important to consider because it represents one of the biggest shortcomings in all tests of this type.

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The relationship between crack growth rate per load cycle, da/dN (where a is the crack length, and N represents the number of load cycles) and fracture mechanics parameter, the stress intensity factor range, ΔK, has to be known.

2. PARIS' LAW UNDER VARIABLE LOADING

Most modifications of Paris' law deal only with single mechanisms of departure from the ideal conditions: threshold limits, both fatigue limit and crack propagation threshold, crack closure, short cracks, among others. The case of short cracks is one of the most well-known since Paris' law can significantly underestimate their rate of growth, and a large number of ad hoc laws reflect the fact that there is not a single type of short-crack deviation. Some authors have suggested a classification of cracks, see [4], as follows:

- microscopic short crack (microstructurally small) for which continuum mechanics breaks down and microstructural fracture mechanics is needed, this is perhaps the most complex category, since crack deceleration or self-arrest is very dependent on the grains size and orientations, and possible decelerations or ''minima'' in da/dN and multiple small-crack curves can be found;
- physically small crack (mechanically small) compared to the scale of local plasticity, for which Elastic-Plastic Fracture Mechanics (EPFM) is needed; da/dN to crack tip decohesion (from knowledge of the cyclic stress-strain curve), and thence to the bulk plastic strain field that occurs, for example, under high strain fatigue;
- macroscopic long crack, growth phase described by Linear Elastic Fracture Mechanics (LEFM) [4].

During cyclic loading, the crack can initiate from existing damage at maximum values of stress, well below quasi-static fracture toughness. The fatigue crack growth rate is defined as a function of the stress intensity factor range ΔK, according to Paris' law [3,5], also popularly known as the Paris–Erdogan equation. Paris' law is a crack growth equation that gives the rate of growth of a fatigue crack:

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

where C and m are material parameters. These constants are related to the fatigue properties, material microstructure, stress, frequency, cyclic loading, and applied temperature. The constant m is usually between 2 and 4, near 4 for metallic materials. For materials with low static fracture toughness, the value of material parameter m can be as high as 10.

The stress intensity factor range, ΔK, is defined as

$$\Delta K = K_{\max} - K_{\min} \tag{2}$$

K_{max} and K_{min} are maximum and minimum stress intensity factors corresponding to the maximal load and minimal load, P_{max} (or maximal nominal stress, σ_{max}) and minimal load, P_{min} (or minimal nominal stress, σ_{min}) in a cycle.

In variable loading of constant amplitude, condition after a determined number of cycles N the crack will initiate, and also crack will propagate if the fatigue threshold, ΔK_{th}, is exceeded. The empirical law of crack growth, expressed by equation (1) and presented in Figure 1 as a sigmoidal curve, is the most frequently used form for the characterization of crack growth rate for a broad spectrum of engineering materials and testing conditions of high strength low-alloy steel (HSLA).

The diagram in Figure 1 shows three different regimes of crack growth.

For analysis, the fatigue life of welded structures can be divided into two parts: crack initiation phase (regime A) and propagation phase (regime B). Fatigue crack propagation behavior is typically described in terms of crack growth rate or crack length extension per cycle of loading (da/dN) plotted against the stress intensity factor range or the change in stress intensity factor from the maximum to the minimum load [6].

In regime A (initiation) crack growth is smaller than one lattice spacing per cycle, connected to a threshold stress intensity factor range ΔK_{th}. Regarding ΔK_{th}, the crack either does not grow or grows very slowly, followed by a very steep increase of crack growth rate per load cycle with stress intensity factor range. In regime B in Fig. 1 (propagation) the central portion of the crack growth curve is linear in the log-log scale. Paris' law (1) is applied only on the segment of the growth curve related to stable fatigue growth. Linear elastic fracture mechanics (LEFM) condition essentially deals with crack propagation in this region, which is commonly described by the crack growth equation proposed by Paris and Erdogan. The crack propagates fast to the final fracture, after reaching the critical stress intensity factor value K_c (regime C) [3,7].

3. EXPERIMENTAL PROCEDURE

The material used in the current experimental investigation was welded joint of high-strength low-alloy steel (HSLA) Nionikral-70 (NN-70), designed for ship structures and pressure vessels. HSLA is designed to provide specific desirable combinations of properties, such as strength, toughness, formability, weldability, and corrosion resistance. The effect of the alloy addition is to raise the yield point of the steel in the as-rolled condition to a level substantially higher than that of the structural carbon grades and at the same time provide weldability and formability. HSLA steels were originally developed in the 1960s for large-diameter oil and gas pipelines. The oil & gas sector is still a market where the most important applications for HSLA steels are found, but the automotive and the offshore & onshore structural engineering sectors now consume significant quantities of these alloys. Also, high-strength low-alloy steels provide better mechanical properties compared to carbon steel. Grain size is reduced to reduce pearlite structure, increasing the material's yield strength.

HSLA steels are available today with traditional ferritic-pearlitic, bainitic, martensitic, and multiphase microstructures, each available in hot- or cold-rolled steels. The exceptions are the controlled-rolled steels with an acicular ferrite microstructure and the dual-phase steels with martensite dispersed in a matrix of polygonal ferrite.

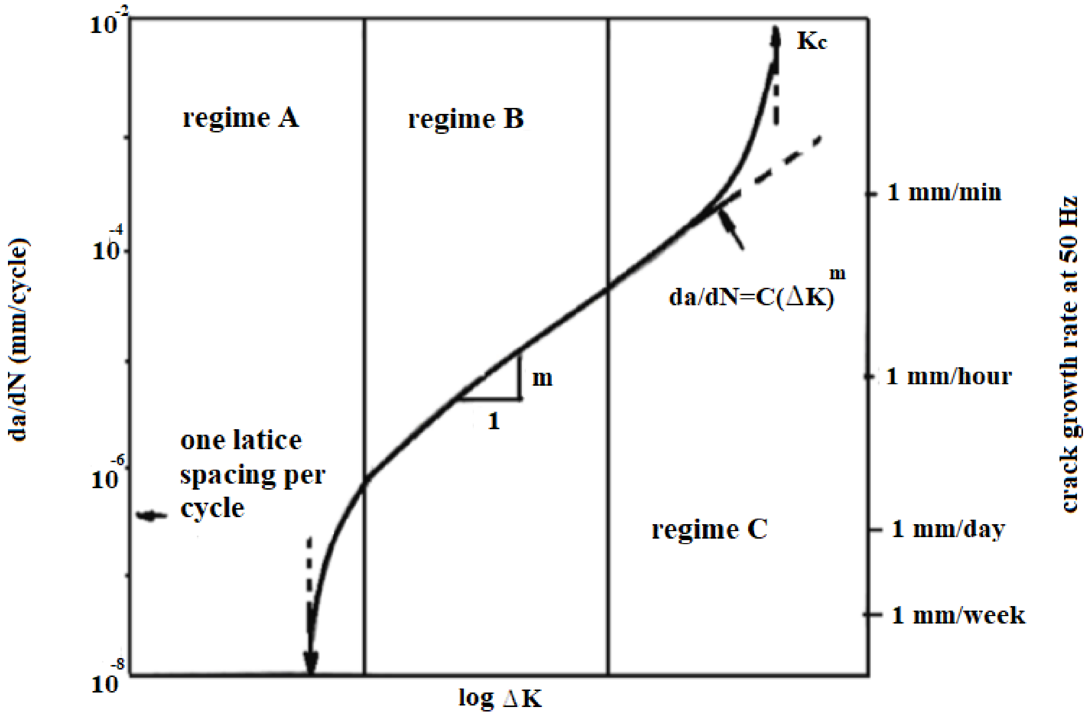

Figure 1. Different regimes of stable fatigue crack propagation [3]

These two types of HSLA steels use the formation of eutectoid structures for strengthening, while the ferritic-pearlitic HSLA steels generally require strengthening of the ferrite. Pearlite is generally an undesirable strengthening agent in structural steel because it reduces impact toughness and requires higher carbon contents. Moreover, yield strength is largely unaffected by a higher pearlite content.

Typical elements that are added to achieve this are titanium, copper, niobium, and vanadium. Carbon contents of HSLA steels can be anywhere between 0.05 and 0.25% (in mass content) to retain formability and weldability. These steels are produced under dozens of different trade names and are covered by a number to ASTM, SAE, and military specifications. General characteristics are similar, but the various grades may be categorized in a general way according to their resistance to atmospheric corrosion. The chemical composition of NN-70 is given in Table 1.

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

NN-70						
C	Si	Mn	P	S	Cr	Ni
0.106	0.209	0.220	0.005	0.017	1.258	2.361

Mechanical properties (NN-70) of the welded joint are given in Table 2. The yield strength of contemporary HSLA steels ranges from 260 MPa to over 1000 MPa.

Table 2. Mechanical properties of NN-70

Material	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
NN-70	645	914	22.4

The technology of manufacture and thermomechanical processing, of Nionikral-70 steel, is the result of joint research from the Military Technical Institute in Belgrade (VTI) and Ironworks Jesenice from Jesenice, in the early 1990s. Steel is produced in the electric furnace, cast in plates, subsequently rolled into slabs, and then into sheets of various thicknesses. Due to some of its characteristics, it is classified among fine-grained steels.

The process of hardening is the combination of classical improvement (quenching and tempering) with grain refinement by selected chemical composition, microalloying, and appropriate deposition.

Test specimens are made of parts of the plates NN-70 welded by the process of manual metal arc welding (MMA). The properties of weld metal of NN-70 largely depend on the selection of an adequate electrode, in this case for filling the K groove or in other words depending on filler material. Therefore, the plates NN-70 were welded by the overmatching effect using the EVB 75 electrode (the chemical composition is given in Table 3.) from the company "Elektrode Jesenice" from Slovenia. EVB 75 is an alloyed basic electrode for welding fine-grained steels and high-strength steels.

The specimens used in this experiment 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. Specimen dimensions are length L=55 mm, width W=10 mm, and thickness B=10 mm, with 2 mm deep notch, Fig. 2.

Tests for determining the fatigue crack growth rate da/dN and fatigue threshold ΔK_{th} are performed on resonant high frequency CRACKTRONIC pulsator, Fig. 3, in load control conditions [7,8].

Table 3. Chemical composition of EVB 75 (% wt)

EVB 75					
C	Si	Mn	Cr	Ni	Mo
0.06	0.45	1.5	0.45	2.2	0.45

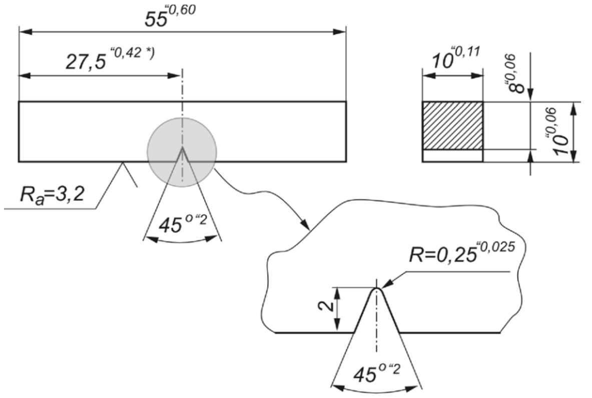

Figure 2. Charpy specimen for determining fatigue crack growth rate

Figure 3. CRACKTRONIC pulsator

Tests 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 [9], measuring 5 mm length, located on the specimen face surface, Fig. 4.

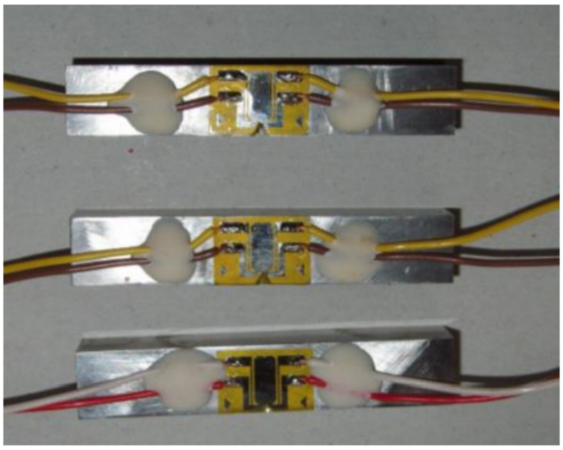

Figure 4. Strain gauge RUMUL RMF A-5 located on the specimen face surface

Strain gauges RUMUL RMF A-5 of 5 mm length are cemented on machined specimens, allowing crack growth monitoring by FRACTOMAT device, based on the electrical potential of gauge and connected with instrumentation, Figure 5. The measuring gauge, a thin resistant measuring foil, is cemented on the specimens in the same way as classical strain gauges. As the crack grows under the measuring foil causing it to rip, it traces the fatigue crack tip, changing foil electrical resistance linearly with the crack length [1,10].

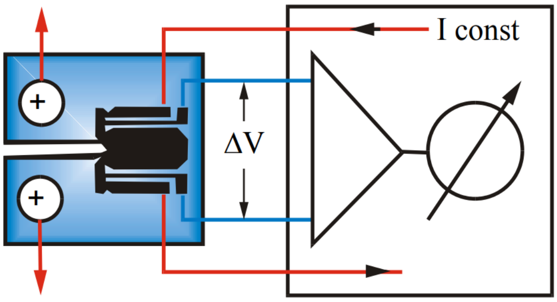

Figure 5. Scheme of measurement foil and crack growth detection [9]

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, ΔP, should be added to the fatigue crack growth rate for current crack length a [7,11].

According to the standard ASTM E647 [12] for determining the stress intensity factor range, the formula below is used:

$$\Delta K = \frac{\Delta P \cdot L}{B\sqrt{W^3}} f\left(a/W\right) \tag{3}$$

where are [13,14]:

L – the distance between supports, mm;
B – specimen thickness, mm;
W – specimen width, mm, and
a – crack length.

$$f\left(a/W\right) = \\ = \frac{3\sqrt{\frac{a}{W}}\left[1.99 - \frac{a}{W}\left(1-\frac{a}{W}\right)\left(2.15 - 3.93\frac{a}{W} + 2.7\left(\frac{a}{W}\right)^2\right)\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}} \tag{4}$$

Fatigue crack growth rate is determined based on obtained relationships of crack length a–number of cycles N [15,16]. Obtained dependence curves a–N is used as the basis for determining fatigue crack growth rate, da/dN. Results are presented in diagram log(da/dN) vs. logΔK, in Fig. 6 for parent metal (PM), weld metal (WM), and heat-affected-zone (HAZ).

The presented diagram shows that the location of the V-2 notch and cracks initiation positioning affect fatigue threshold value, as well as on coefficient C and exponent m in the Paris equation [17,18].

The results in Table 4 show values of the fatigue threshold ΔK_{th} and material parameters-coefficient C and exponent m for fatigue crack growth.

Table 4. Values of fatigue crack growth parameters of welded joint NN-70

Crack location	ΔK_{th} (MPa $\cdot m^{1/2}$)	Coefficient C	Coefficient m
PM	14.93	$3.74 \cdot 10^{-10}$	3.43
WM	12.85	$1.53 \cdot 10^{-11}$	4.47
HAZ	13.70	$5.90 \cdot 10^{-10}$	3.35

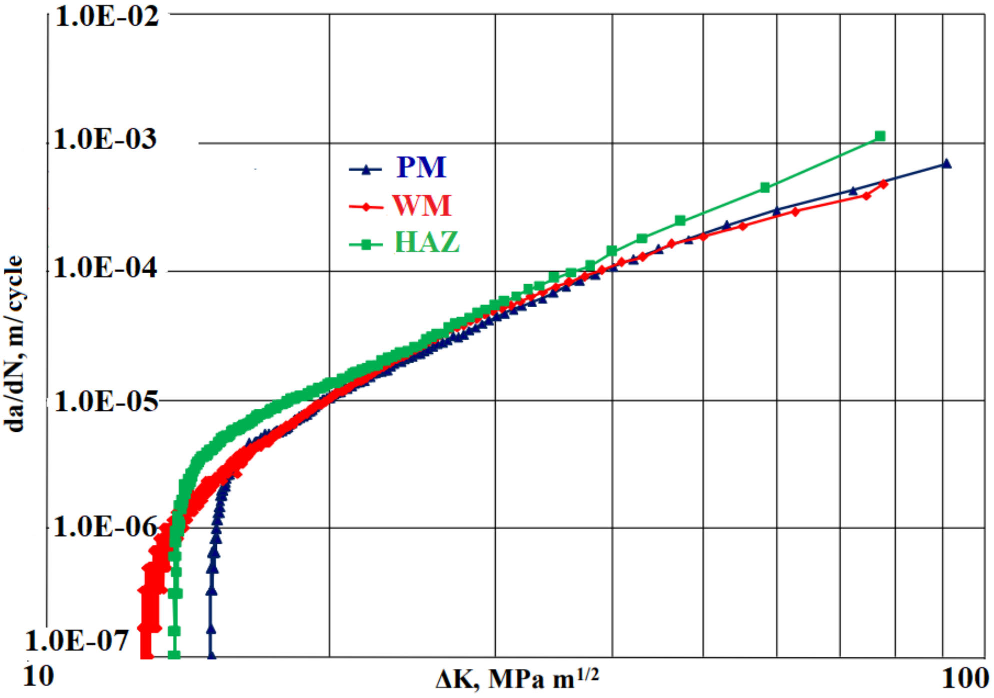

Figure 6. Crack growth rate da/dN vs. stress intensity factor range ΔK for welded joint constituents

4. ANALYSIS OF TESTING RESULTS

In this paper real data was used to estimate Paris law parameters. In Fig. 6 the linear central part of the curve is covered by the Paris law and is most important since it allows to make a difference between low fatigue crack growth rates close to the fatigue threshold, and high rates (K_{Ic}), when a fracture occurs.

Values of fatigue threshold ΔK_{th} obtained for parent metal (ΔK_{th}=14.93 MPa·m$^{1/2}$) are higher than corresponding test values for specimens notched in weld metal (ΔK_{th}=12.85 MPa·m$^{1/2}$) and heat-affected-zone (ΔK_{th}= 13.70 MPa·m$^{1/2}$).

In the region of Paris law validity, where lowest fatigue crack growth (highest crack propagation resistance) has parent metal (PM) then weld metal (WM) while the lowest crack propagation resistance has a sample with the crack in heat-affected-zone (HAZ).

Welded joint NN-70 constituent behavior, and also of the entire welded joint should be connected to the change in curve slope in the region of Paris law validity and as a rule, materials exhibiting lower fatigue crack growth rate have a lower slope on the da/dN–ΔK diagram. In this case, a sample of the specimen with the crack in parent metal (PM) has the lowest slope while a sample of the specimen with the crack in heat-affected-zone (HAZ) has the highest slope in the da/dN–ΔK diagram, shown in Figure 6.

However, the worst crack propagation resistance has a sample with the crack in the heat-affected zone. For heat-affected-zone, the highest fatigue crack growth rate is present compared to parent metal and weld metal, which is directly related to the influence of the heterogeneity of the microstructure of the heat-affected-zone on the fatigue crack growth rate.

The maximum fatigue crack growth rate is expected when the stress intensity factor range approaches the fracture toughness at plane strain followed by brittle fracture of the material.

Based on analysis of the results and discussion of experimental tests it can be concluded that the welded joint of high strength low-alloy steel (HSLA) geometrically imperfect shape especially observed in the determination fatigue crack growth rates of welded joint NN-70.

Because of the experimental results, it is believed that this method can effectively guide the anti-fatigue design of practical engineering structures and has the potential to fill the gap in the design of strength-mismatched welding structures in international codes and standards. In general, the practical application of this testing is reflected in the experimental contribution to the assessment of the behavior of the welded joint and the components of the welded joint in the presence of cracks. Upon reaching the stress intensity factor value, unstable crack growth occurs, which can be practically used to determine the measure of fracture resistance. On the other hand, the range of stress intensity factors in the load cycle is successfully used to define the law of crack growth rate during fatigue fracture [19].

5. CONCLUSION

Assessment of structural integrity is a useful tool to avoid damage of welded structures. Proper evaluation of fatigue crack propagation life is necessary for the assessment of structural integrity.

Paris curve was originally thought of as universal law, in the sense that should be able to provide a universal description of fatigue. The experimentally observed deviations led to a proliferation of modified fatigue criteria, very often represented by power laws. Therefore, if on the one hand, the research efforts were directed towards the extension of the original fields of application of the Paris representations of fatigue [20, 21], on the other hand, the fundamental problem of finding the link between the cumulative fatigue damage and the fatigue crack propagation approaches remained largely unsolved, as previously mentioned in [22, 23 and 24].

In the present contribution, crack growth data of weld structures under fatigue loads is necessary for the application of fracture mechanics methods to evaluate the effects of weld and calculate the residual life of weld structures. Therefore, the investigation of fatigue crack growth behavior of weld structures is of significant importance. Considering fatigue crack growth in welded joints, the percentage of the crack propagation phase in the total fatigue life is very much dependent on the quality of the weld comprising weld geometry, initial defects in the weld, weld residual stresses, and local stress conditions. Since welding defects can frequently exist in the vicinity of weldments, local stress concentrations around discontinuities and weld defects are fairly common.

In general, predicting the fatigue life for constant amplitude loads, regarding the number of cycles required for crack growth from initial to critical crack length, is today the basis for assessing the integrity of any structure, including pressure vessels and ship structures. It is of great interest to study the crack propagation conditions to design and plan a maintenance strategy based on crack growth management, which ensures e.g. safety of the ships and pressure vessels.

The application of the Paris equation is particularly suitable for the fatigue of structures made of high-strength materials, especially HSLA steel.

Thus, the influence of notch location and crack propagation direction, or the structural heterogeneity of welded joint constituents on fatigue crack growth rate da/dN is directly connected to the obtained parameters of the Paris law, coefficient C and exponent m. Materials exhibiting lower fatigue crack growth rate has a lower slope on the da/dN–ΔK diagram, at room temperature.

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. Further work on this experiment can be divided into subjects that involve minor efforts or changes to the established program:

- control of the crack increment size based on the changes in stress intensity at the crack tip and
- multi crack propagation.

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NOMENCLATURE

da/dN	crack growth rate per load cycle
a	crack length
N	the number of load cycles
ΔK	stress intensity factor range
ΔK_{th}	range of threshold stress intensity factor
C,m	material parameters
$K_{max,} K_{min}$	maximum and minimum stress intensity factors
L	distance between supports
B	specimen thickness
W	specimen width

ПРИМЕНА ПАРИСОВОГ ЗАКОНА У УСЛОВИМА ПРОМЕНЉИВОГ ОПТЕРЕЋЕЊА

С. Булатовић, В. Алексић, Љ. Миловић,
Б. Зечевић

За сигурност заварених конструкција током експлоатације најважније су карактеристике које описују појаву и раст прслина под утицајем променљивог оптерећења. Иницијација и раст прслине изазване променљивим оптерећењем предмет су многих истраживања. Рад приказује одређивање параметара заморне прслине за конституенте заварених спојева израђених од нисколегираног челика повишене чврстоће. Парисов закон раста прслине успоставља зависност величине делујућег променљивог оптерећења, односно, одговарајућег опсега фактора интензитета напона и раста прслине по циклусу. Резултати показују да положај зареза и иницијација прслине утичу на вредности распона напона за границу замора ΔK_{th} и на параметре Парисове релације.