Experimental examination of fatigue life of welded joint with stress concentration

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ABSTRACT. This paper presents results of experimental examinations of stress concentration influence to fatigue life of butt welded joints with K-groove, produced from the most frequently used structural steel S355J2+N. One group of experiments comprised examinations carried out on the K-groove specimens with stress concentrators of edged notch type. Specimens with short cracks (limited length of initial crack), defined on the basis of the experience from fracture mechanics by the three points bending examinations, have been examined according to standard for the determination of S-N curve, and aimed to determine fatigue strengths for different lengths of initial crack and Relationship between fatigue strength and crack length. Other group of experiments comprised examinations of specimens with edge notch, prepared in accordance with ASTM E 399 for three points bending, in order to establish regularity between crack growth and range of exerted stress intensity factor aimed to determine resistance of welded joint to initial crack growth, namely fatigue threshold (ΔK_{th}).

KEYWORDS. Welded joint; Stress concentration; Crack; Fatigue strength; Crack growth rate; Fatigue threshold.

INTRODUCTION

Safety of welded structures depends mainly on shapes of welded joints, stress concentration, heterogeneity of structural and mechanical properties of base metal (BM), heat affected zone (HAZ) and filler metal (FM), residual stresses and strains due to welding procedure and imperfections in welded joints. Welded joints, therefore, are frequent locations of fatigue failures.

Fatigue in welded structures commonly initiates in stress concentration area. Significant reduction of fatigue durability is related to theoretical stress concentration factor which actually is ratio of maximal and nominal stress ($k_t = \sigma_{max}/\sigma$). The stress concentration factor data for certain types of welded joints which are available in literature are obtained by the method of photo-elasticity, and more recently also by the finite elements method.
According to data of International Institute of Welding (IIW), alongside the fractures due to fatigue as the consequence of design mistakes, significant number of fractures also has been stipulated by imperfections in welded joints in structures subjected to numerous variable loads of relatively low level.
Premature fracture or damage of welded structures is induced by simultaneous influence of numerous technological, metallurgical, designing and exploitation factors, which can explain wide dispersion of fatigue strength values for welded joints, for the various stress amplitude ratios ($R=\sigma_{min}/\sigma_{max}$).
Fatigue behavior of welded joints and constructions are commonly obtained by examinations of standard specimens or model elements with sinusoidal load (one-step load), while level of mean load or ratio of loads remains constant during examination. Examination results are shown as a fatigue diagram, so-called Weller curve.
Cracks or crack-like defects frequently appear during manufacturing of products or in process of elements mounting, especially in the case of welded structures, due to mistakes in manufacturing procedure, unfavorable shaping, structural stress concentrators and conditions of structure loading.
Characterization of fracture as multiphase process of crack initiation and growth include also different initial stages, which imply possibilities for further crack growth, as shown in [1].
Crack growth basically can be: stable, subcritical or unstable, whereas possibilities of crack growth may vary following one of the paths from 1 to 8, Fig. 1.

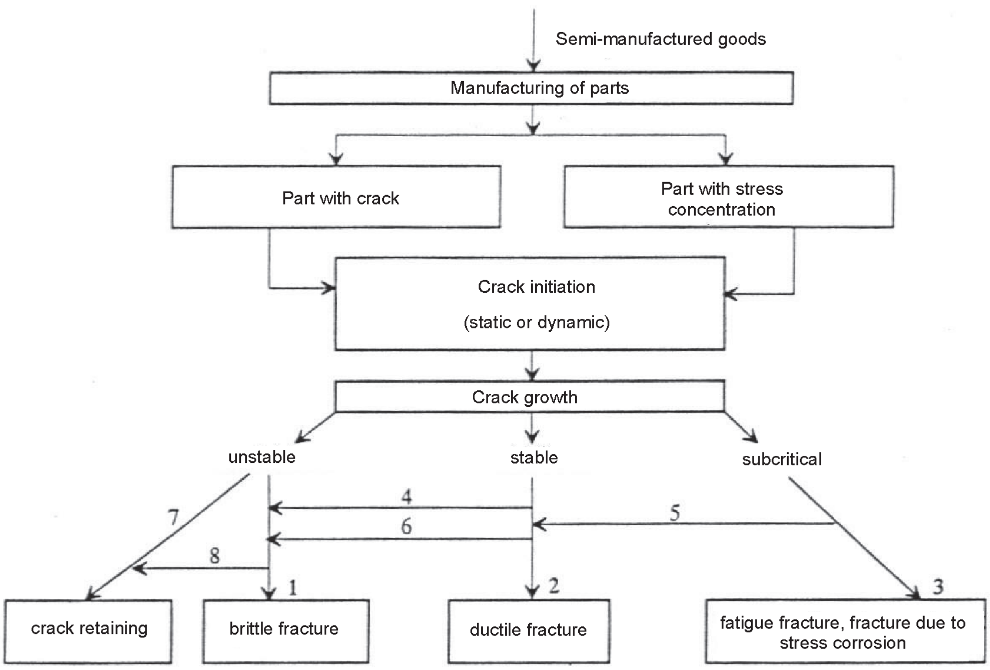

Figure 1: Possibilities of crack growth.

Stable crack growth originates in cases of constant energy consumption and mostly leads to macroscopic ductile fracture. Subcritical (successive) crack growth appears when process of stable crack growth appears in longer period of time. Crack growth could be finished also with its transition to stable or unstable growth. Unstable crack growth occurs with high speed without energy consumption and it leads to macroscopic brittle fracture. Nevertheless, in some cases unstable crack growth stops, phenomenon known as a crack arrest. Therefore, significant experimental and theoretical analyses are directed to establish functionalities that hold for this region, so-called region of fatigue threshold.
Another intensively studied domain is behavior of structures with short cracks, aimed to assess their influence to integrity. Concept of short cracks is connected to area of crack lengths which cannot be recorded by existing nondestructive testing methods, and from the viewpoint of material researcher length of short cracks shouldn't exceed dimensions of micro structural grain size. Therefore, short cracks are:

– cracks with length which is comparable with dimensions of microstructural grain size,
– cracks which dimensions are proportional to local plastic zone, i.e. short crack with dimensions from 0.1 up to 1.0 mm for structural steels [2].

INFLUENCE OF STRESS CONCENTRATION ON FATIGUE STRENGTH OF WELDED JOINTS

Welded joints in real constructions are areas of high stress concentration level, especially in the places with imperfections, such as incomplete root penetration, undercuts or cracks.

Ratio of the maximal main stress σ_{max}, which is established in the minimal cross-section area and nominal stress σ represents stress concentration factor k_t:

$$k_t = \frac{\sigma_{max}}{\sigma} \quad (1)$$

Factor k_t for the same element shape depends on loading type and it is maximal in the case of tension, somewhat smaller in the case of bending, and minimal in the case of torsion.

In the case of variable load, notch reduces fatigue strength in all metals. Nevertheless, reduction of fatigue strength is not as significant as influence of k_t, which is thus not used for variable loads, but only for static loads. Fatigue notch factor k_f is used to characterize influence of notch to fatigue strength, and it represents the ratio of smooth specimen fatigue strength S_f and notched specimen fatigue strength S_z.

$$k_f = \frac{S_f}{S_z} \quad (2)$$

Factor k_f is determined by experiment. Its magnitude, for uniaxial stress state, depends on welded joint shape and notch dimensions, material, part dimensions and magnitude of variable load. Relation between k_t and k_f factors is defined by stress concentration sensitivity factor q, which is given by the expression:

$$q = \frac{k_f - 1}{k_t - 1} \quad (3)$$

Steel sensitivity to stress concentration is increased with the increase of tensile strength, yield stress and hardness. Stress concentration factors are minimal for butt welds, depending on plate thickness, joint shape and welding procedure, k_f = 1.1 – 3.0, for fillet welds k_f = 2 - 8, and for overlapping joints k_f = 2 – 7. Significant fluctuation of notch factor for one type of welded joint, which is predetermined by the joint shape and joint imperfections, sometimes lead to rapid decrease of fatigue strength.

	Yield stress R_{eH} [MPa]	Tensile strength R_m [MPa]	Elongation A5 [%]
Base metal S355J2+N	368	512	26
Electrode "Garant" E 43 4B 110 20 (H)	480	550	35

Table 1: Mechanical properties of base metal and electrode.

FATIGUE EXAMINATION OF K-GROOVED WELDED JOINTS

Program of experimental examinations of characteristic welded joints is based on research plan aimed to establish relationship between fatigue strength of smooth specimens and notched specimens, as well as to investigate mechanism of crack appearance and crack propagation in welded joints.

Mechanical properties of base and filler metal, according to manufacturer's data, are given in Tab. 1. Welding of specimens has been carried out by using approved welding procedure specification.

Results of fatigue strength examinations on smooth specimens

Fatigue examination of smooth specimens have been carried out on high frequency pulsator "Amsler" which is used for examinations by sinusoidal alternative cyclic loads with range of ± 50 kN, whereby in dependence on load magnitude, frequency up to 250 Hz can be achieved. Obtained value of fatigue strength is S_f=420 MPa, Fig. 2.

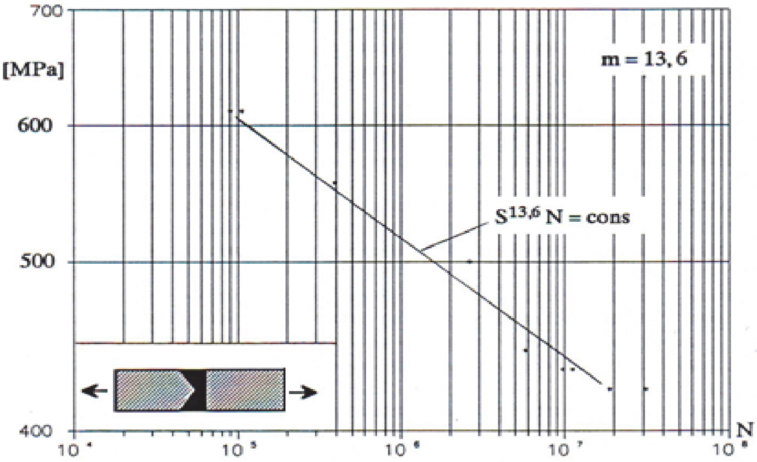

Figure 2: S-N Relationship for K-grooved butt weld.

Examinations of specimens with different lengths of edge notches by three points bending have been performed in order to determine fatigue strength of welded joints with short cracks (with limited length of initial crack), in other words to confirm the stress which cause crack closure due to arisen plastic zone on crack tip.

Taking into account that mentioned experiments are not simple but very expensive, examinations have been performed only for the area of expected fatigue strength with set of 6 specimens, for the five different classes of initial notches. Stress concentrators have been made in zone of fusion of base metal and weld metal. This has been enabled owing to existing results of smooth specimen examination results. Specimen dimensions and the position of notch are shown in Fig. 3, and sizes of initial notches are given by Tab. 2. Data about examination conditions and properties of fatigue strength for every class of specimens is given in Tab. 3. Examination results are shown in Fig. 4 – 8.

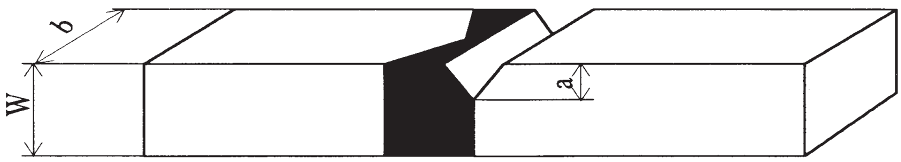

Figure 3: Dimensions of specimen and notch position.

Statistic analysis of examination results has been carried out, aimed to establish relationship between critical length of short crack and fatigue strength. It came out that relationship a_c-S_f in double logarithmic coordinate system can be presented by straight line, Fig. 9.

Relationship between critical crack length and fatigue strength, shown in Fig. 9, can be expressed as exponential function in logarithmic form:

$$\log a_c = \log C_1 + C_2 \log S_z \tag{4}$$

Specimen class	Initial notch	Specimen dimensions			Number of specimens
	a [mm]	W [mm]	B [mm]	L [mm]	
1	0.250	9.90	9.50	40	6
2	0.351	9.79	9.60	40	6
3	0.591	9.90	9.50	40	6
4	0.723	9.90	9.70	40	6
5	1.125	9.85	9.80	40	6

Table 2: Geometric characteristics of specimens and sizes of initial notch.

Specimen class	a [mm]	ΔM [N·mm]	Δσ [MPa]	R -	f [Hz]	σ_a [MPa]	σ_m [MPa]	S_z [MPa]
1	0.250	19200	157.48	0.5	230-240	81.03	236.23	315
2	0.351	16100	141.24	0.5	230-240	70.62	211.86	282
3	0.591	13600	124.41	0.5	230-240	62.21	186.62	249
4	0.723	12200	112.86	0.5	230-240	56.43	169.30	226
5	1.125	9500	97.47	0.5	230-240	48.73	146.20	195

Table 3: Examination conditions and fatigue strength properties.

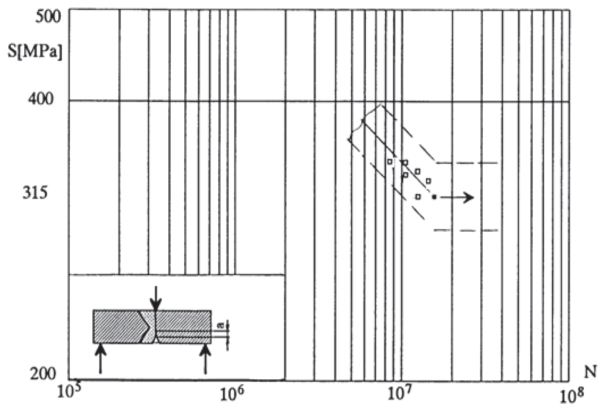

Figure 4: S-N Relationship for specimens with initial crack a = 0.25 mm.

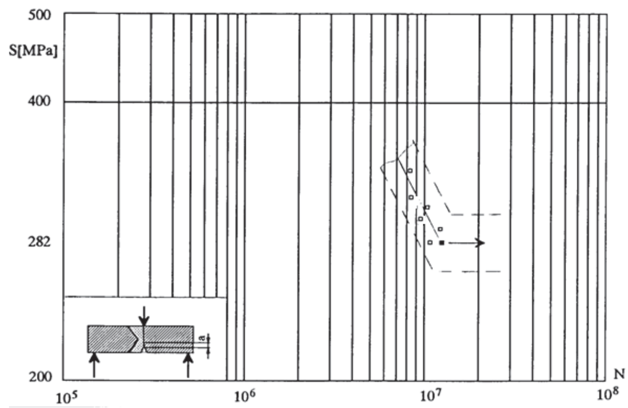

Figure 5: S-N Relationship for specimens with initial crack a = 0.351 mm.

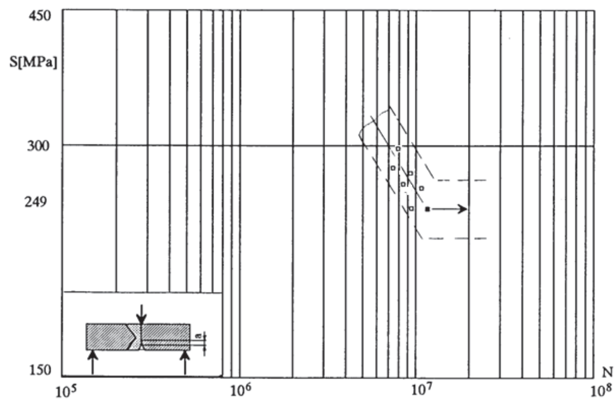

Figure 6: S-N Relationship for specimens with initial crack a=0.591 mm.

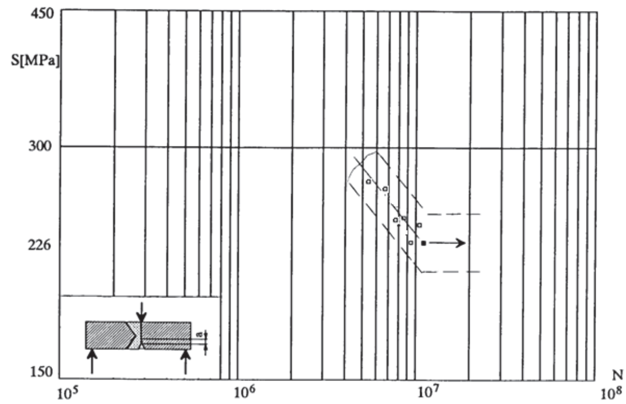

Figure 7: S-N Relationship for specimens with initial crack a= 0.782 mm.

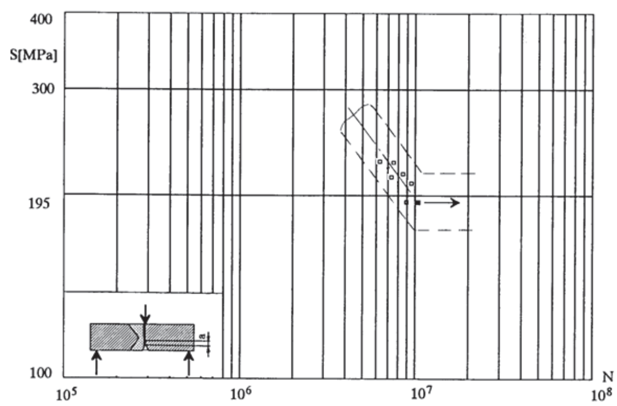

Figure 8: S-N Relationship for specimens with initial crack a= 1.125 mm.

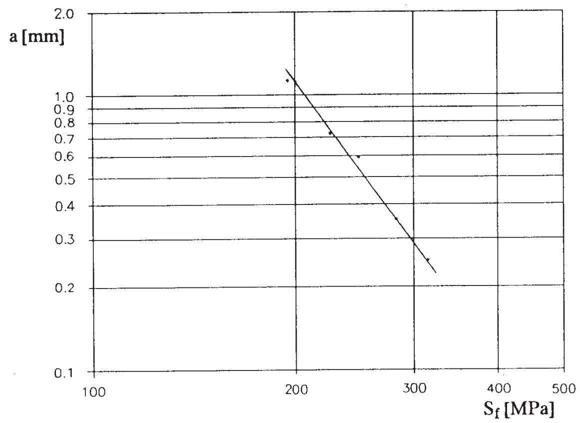

Figure 9: Relationship between critical crack length and fatigue strength.

Procedure of calculating coefficients C_1 and C_2 by the method of the minimal square deviations is based on the condition that sum of obtained data square deviations from functional relation should be minimal:

$$F(C_1, C_2) = \sum_{i=1}^{n} \left(C_2 \log S_z + \log C_1 - \log a_c \right)^2 = \min \tag{5}$$

Parameters C_1 and C_2 should be determined from following equation in order to get minimal value of function $F(C_1,C_2)$:

$$\frac{\partial F(C_1, C_2)}{\partial C_1} = 0; \; \frac{\partial F(C_1, C_2)}{\partial C_2} = 0 \tag{6}$$

In this way, system of equations for calculation of coefficients C_1 and C_2 is obtained:

$$\begin{aligned} & n \log C_1 + C_2 \sum_{i=1}^{n} \log S_{zi} = \sum_{i=1}^{n} \log a_{ci} \\ & (\log C_1) \sum_{i=1}^{n} \log S_{zi} + C_2 \sum_{i=1}^{n} (\log S_{zi}) = \sum_{i=1}^{n} \log S_{zi} \cdot \log_{ci} \end{aligned} \tag{7}$$

where "i" represents specimen number (from 1 to 5). Values needed to solve the equation system (7) are given in Tab. 4. Relation between critical length of short crack a_c (given in meters) and fatigue strength $S_{f,z}$ (given in MPa) is:

$$a_c = 18960 \, S_z^{-3.15} \tag{8}$$

i	$S_{zi,}$ [MPa]	a_{ci} [mm]	log S_{zi}	log a_{ci}	(log S_{zi})	log S_{zi} log a_{ci}
1	195	1.125	2.2898831	0.0511525	5.2435646	0.1171332
2	226	0.723	2.3535816	-0.1408617	5.5393463	-0.3315295
3	249	0.591	2.3958992	-0.2284125	5.7403329	-0.5472533
4	282	0.351	2.4509785	-0.4546928	6.0072956	-1.1144422
5	315	0.250	2.4982637	-0.6020599	6.2413215	-1.500414
Σ			11.988606	-1.3748744	28.771858	-3.3801961

Table 4: Values for solving the equation system (7).

When substitute value fatigue strength of K-grooved butt welds, S = 420 MPa (Fig. 2), in Eq. 8 critical length of short crack will be a_c=0.1 mm. On the basis of experimental examinations, values of fatigue notch factors k_f for different initial fatigue cracks calculated by Eq. 2, are given in Tab. 5.

Specimen class	Initial fatigue crack, a [mm]	Fatigue notch factor, k_f
1	0.250	1.33
2	0.351	1.49
3	0.591	1.76
4	0.723	1.86
5	1.125	2.15

Table 5: Values of fatigue notch factors.

Results of fatigue crack growth testing

Fatigue crack growth testing has been performed by the controlled bending force in three points, with asymmetrical load R= F_{min}/F_{max} = 0.5, on the specimen with edge notch. Testing has been carried out using high frequency pulsator "Cracktronic", and gathering of crack growth data has been done by using measuring foils ARM A-10. Number of cycles for the every 0.1 mm growth of crack has been recorded during experiment. Crack growth has been observed by magnifying glass (24 x). On the basis of these records, diagram a - N, Fig 10, has been drawn. Curve a - N indicates that fatigue crack grows slowly till a = 1.5 mm, when rapid crack growth occurs for relatively small number of load cycles. Relationship a - N can be taken as uniform, because there is no crack growth deceleration or its abrupt growth. Relationship a - N has been used as the basis for determination of crack growth rate, da/dN. In this paper, crack growth rates have been calculated by using the polynomial method, as defined in ASTM E647. Adequate range of stress intensity factor ΔK, depending on specimen shape, crack length and range of variable force $\Delta F = F_{max} - F_{min}$, has been calculated.
Values of coefficients m and C have been calculated, as they characterize resistance of material to crack growth and define Paris' equation (m=3.516, $C=3.18 \cdot 10^{-12}$). Obtained values for m and C correspond to material class with similar mechanical properties, /3-5/. Relationship da/dN - ΔK is shown in Fig. 11.
On the basis of numerous examinations, which showed that fatigue threshold has appeared for low values of crack growth rate, i.e. in rate range from 10^{-6} up to 10^{-8} mm/cycle, and according to the shape of da/dN - ΔK curve (Fig. 11), one can conclude that value of fatigue threshold is ΔK_{th} = 7.24 MPa, corresponding to crack growth rate of 10^{-8} mm/cycle.

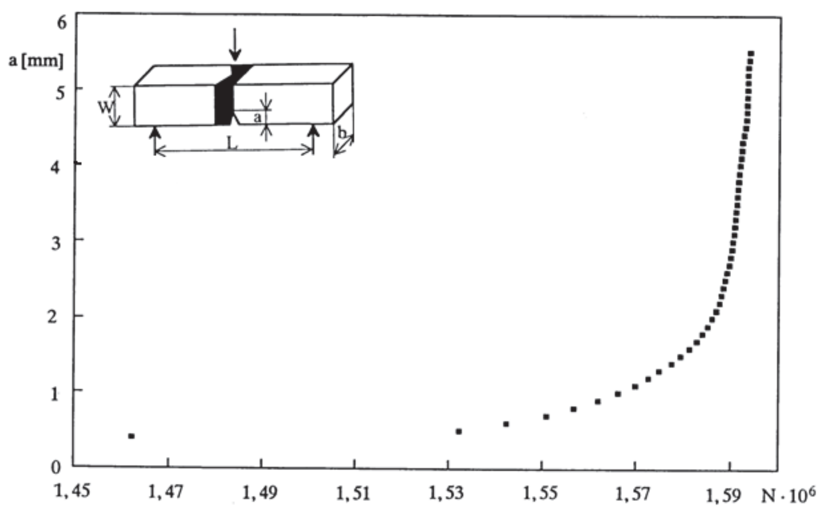

Figure 10: Experimentally obtained a-N curve.

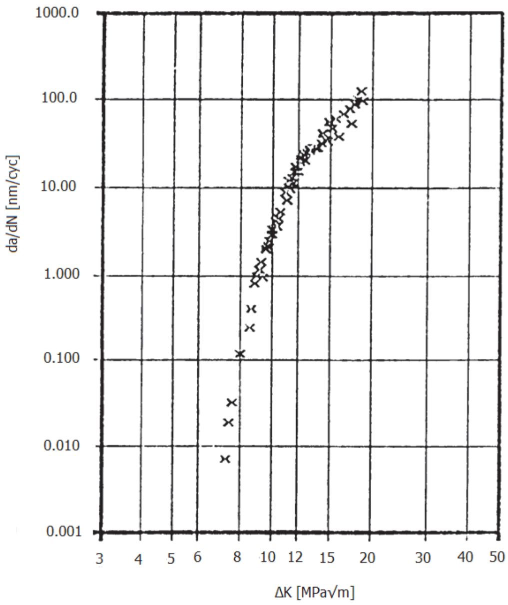

Figure 11: Curve da/dN –ΔK.

Conclusion

Presented research and established mathematical relationship between critical crack length and fatigue strength offer great possibilities for analysis of fatigue behavior of welded joints made from structural steel S355J2+N on the supporting structures of building machines, dredgers, elevators, bridges, supporting structure in power plants, petrochemical and oil industry. In addition to this, presented results enable analysis of welding procedure, significant welding parameters and welding consumable material quality aimed to minimize negative effects of variable load to welded joint, i.e. to implement convenient structure.

Established mathematical relationship between critical crack length and fatigue strength of K-grooved butt welds have general character for structural steels, because it enables evaluation of critical crack length for all welded joints with surface imperfection of undercut type and welded joints with incomplete root penetration.

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