Fatigue Crack Path Development in a One-Sided Restrained Bar with a Rectangular Section and Stress Concentrator under Bending

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ABSTRACT. *The paper presents a crack path development in plane specimens under cyclic bending and the test results for fatigue crack growth in 18G2A steel for three kinds of stress concentrators. The tests were done for constant amplitude of the bending moment with the stress ratio R = - 1 on specimens with the stress concentrators being one-sided sharp and blunt and two-sided sharp notches. It has been found that in the case of sharp notches a fatigue crack path development proceeds according to Mode I paralel to the specimen height or with a slide divergence of the vertical axis. In the case of blunt notched specimens, different crack developments could be observed (they were curved or straight with a slight divergence). The tests showed that the shortest lives of the tested material were obtained with one-sided sharp notch and the longest lives were obtained for one-sided blunt notch under the same loading.*

INTRODUCTION

Theoretical determination of the fatigue crack path according to Mode I is usually based on linearly elastic analysis in a two-dimensional system. In tests we usually use thin sheets (specimens) in the plane stress state [1], understood as two-dimensional elements (their thickness is not taken into account). The observed crack paths are straight lines or smooth curves and most of them are reproducible [2]. Many authors consider the crack paths in the plane for Mode I [3], using small increments of crack propagations in form of straight lines. Conformity between theoretical prediction and experimental data for thin specimens is not always satisfacory [4]. While analysing a crack path growth in a three-dimensional system [5], we are dealing with mixed modes I and III which are intersecting in one point at the initial stage of the crack growth. Theoretical considerations on the crack path development in the case of mixed modes differ from the real ones more often than in the case of two-dimensional systems. In paper [6] the author presents a solution of the problem of long cracks path in metallic welded materials including the second stage of cracking. In the welded pipe joints [6] the fatigue crack growth is usually limited to the toe of weld and we can sometimes observe mixed modes of the fatigue crack growth. The three-dimensional description of the crack path requires a description of the crack growth surface and a family of lines on this surface, which defines successive positions of the crack front. Generally speaking, crack growth in pipe welded joints proceeds usually according to Mode I. It has been observed that the crack growth surfaces are curved and geometrical constraints occur on permissible families of the crack fronts. Theoretical forecast of crack paths in three dimensions of the structure is usually not efficient and in practice we should do some laboratory tests.

The aim of this paper is to analyse the crack growth path in steel specimens with different shapes of the stress concentrators under symmetric bending and influence of the concentrator on the fatigue life.

EXPERIMENTS

Plane specimens of the low alloy higher strength steel 18G2A described in the Polish Standard PN-86/H-84018 were tested. The specimens were cut from the sheet according to the rolling direction. The specimen dimensions were: length l = 120 mm, height b = 20 mm and thickness g = 4 mm (see Fig. 1). The specimens subjected to bending had an external unilateral notches, 5 mm in depth, with the rounding radii ρ = 0.5 and 3 mm as well as two-sided notches, 2.5 mm in depth, with the rounding radius ρ = 0.5 (Fig.1). The notches in the specimens were cut with a milling cutter, the specimen surfaces were polished after grinding.

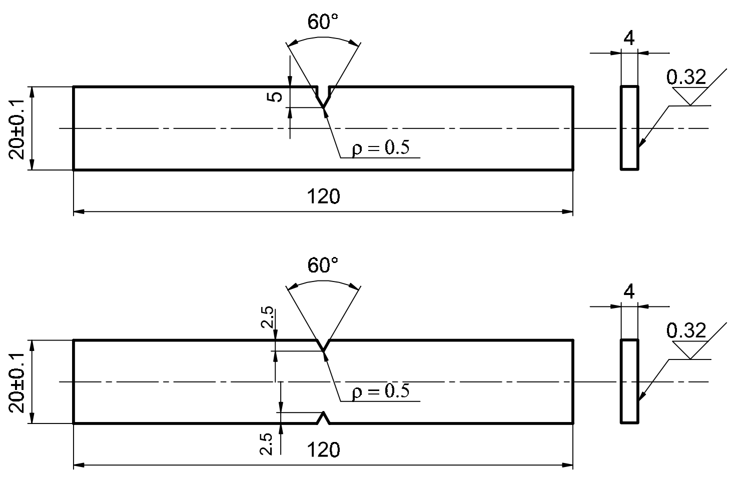

Figure 1. Shapes and dimensions of specimens for tests of fatigue crack growth.

Chemical composition and some mechanical properties of the tested steel are shown in Tables 1 and 2.

Table 1. Chemical composition of 18G2A steel

C-0.2%	Mn-1.49%	Si-0.33%	P-0.023%	Fe
S-0.024%	Cr-0.01%	Ni-0.01%	Cu-0.035%	the rest

Table 2. Mechanical properties of 18G2A steel

Yield stress R_e (MPa)	Ultimate stress R_m (MPa)	Elastic modulus E (GPa)	Poisson`s ratio ν
357	535	210	0.3

The specimens subjected to cyclic bending were loaded with the constant amplitude of the moment M_a = (18.9, 25.4, 35.7) Nm, corresponding to the nominal stress amplitude to the crack initiation σ_a = (126, 169.3, 238) MPa. The stress ratio R = - 1. Tests of bending were performed under loading frequency 28.8 Hz. Crack growth was observed on the specimen surface with optical methods. The tests were done at the fatigue test stand MZGS-100 (Fig.2) [7] enabling realization of cyclic variable histories of bending generating the plane stress state in specimens [8].

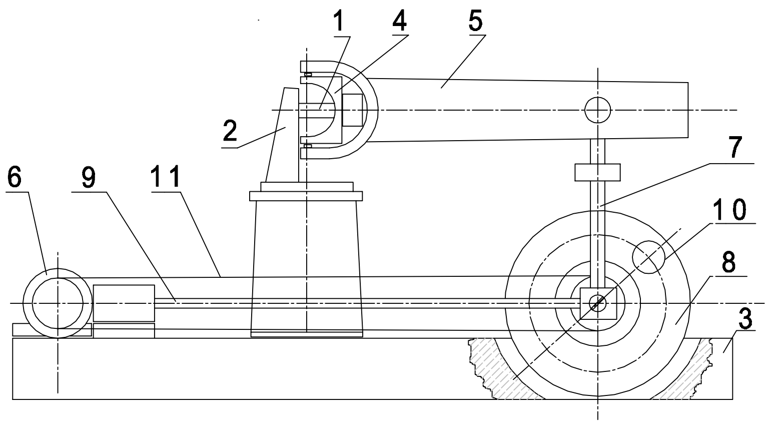

Figure 2. Fatigue test stand MZGS-100, where: 1 - specimen, 2 - rotational head with a holder, 3- bed, 4 - holder, 5 – lever (effective length = 0.22 m), 6 - motor, 7 – lower string, 8 – rotating disk, 9 – flat springs, 10 – unbalanced mass, 11 – driving belt.

The specimen (1) is fixed in the holders (2) and (4). Loading is obtained as a result of the lever (5) motion in the vertical plane, caused by the inertial force of the unbalanced mass (10) on the rotating disk (8) located on the flat springs (9). The fatigue crack growth was measured with a digital micrometer located in a portable microscope. The measurements were done with an accuracy of 0.01 mm and numbers of loading cycles N were registered. The crack length increase at both sides of the specimens in relation to thickness on was uniform. In specimens with sharp two-sided notches a non-uniform crack length increment was observed (the upper part in relation of the lower part) in about 70% cases. The crack length development begins at one side of the specimen height and it develops by about 1 - 2 mm, next a crack occurs at the other side of the specimen height developing up to the material failure. In 30% cases a uniform crack development on both sides of the specimen height was observed.

CRACK PATH DEVELOPMENT

Tests were performed in the two-dimensional system for Mode I. In specimens with the sharp one-sided and two-sided notches the crack paths started in the notch top and it proceeded parallel to the specimen height without any fluctuations (see Figs. 3a and 3 b).

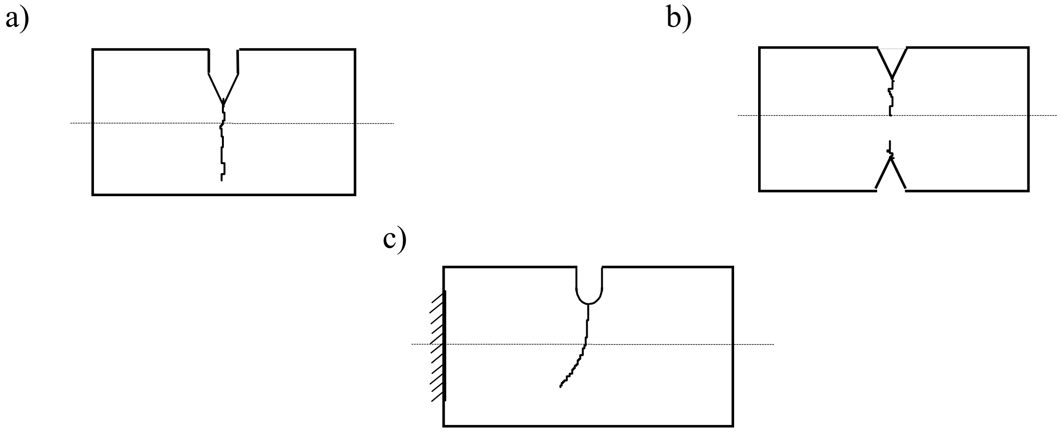

Figure 3. Crack path development in specimens with sharp notches: a) one-sided, b) two-sided and with c) blunt notch.

While in specimens with blunt notches, the crack path development starts in the notch top and proceeds analogically as in the specimens with sharp notches or at a certain angle reaching about 12^{o} (Fig. 3c). It can be caused by the residual stresses occurring under the applied uniaxial loading and causing multiaxial stress state. A theoretical analysis of determination of the crack path was also done for a two-dimensional geometrical model. The analysis was done with the finite element method and the program FRANC2D. The model applied six-nodal triangle-shaped elements. For calculations the same loadings as in experiments were assumed. In numerical calculations low increments of crack propagation in form of straight lines were used. An agreement between theoretical prediction and experimental crack paths was obtained for the specimens with both types of notches (in the cases when the crack proceeded in the same way as in the specimens with the sharp notches).

THE TEST RESULTS AND THEIR ANALYSIS

The paper contains the test results enabling to reflect the phenomena occurring in 18G2A steel during the fatigue crack growth under cyclic bending for various stress concentrators. The test were performed under controlled loading. The results of measurements for different notches and loading are presented in Figs. 4, 5 dna 6 on the graphs a = f (N) where a is the actual crack length measured from the concentrator top after N cycles. Fig. 4 shows how the notch influences the specimen life under the constant amplitude of the bending moment M_a = 25.37 Nm (curve 1 – one-sided sharp notch, K_t = 3.27; curve 2 – two-sided sharp notch, K_t = 3.53 and curve 3 – one-sided blunt notch, K_t = 1.66). From the tests it appears that for the one-sided sharp notch (Fig.4, curve 1) specimen life is the shortest, whereas for the blunt notch (Fig. 4, curve 3) the life is the longest. For the two-sided sharp notch (Fig.4, curve 2) the life is longer than for the one-sided sharp notch. It can be due to the fact that a plastic zone, forming around the crack top causes the crack growth retardation (the occurring residual compressing stresses [1] lead to the crack closing and decrease the fatigue crack rate).

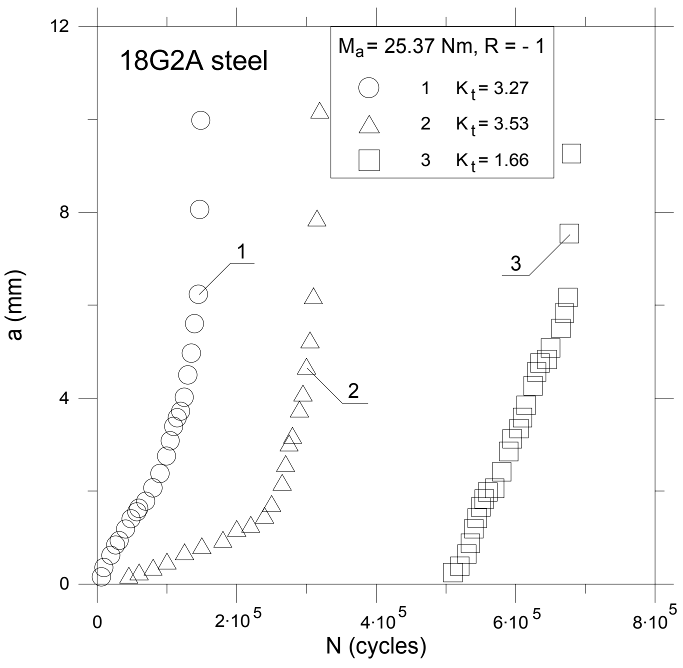

Figure 4. Fatigue crack growth versus a number of cycles for M_a = 25.37 Nm for various stress concentrators.

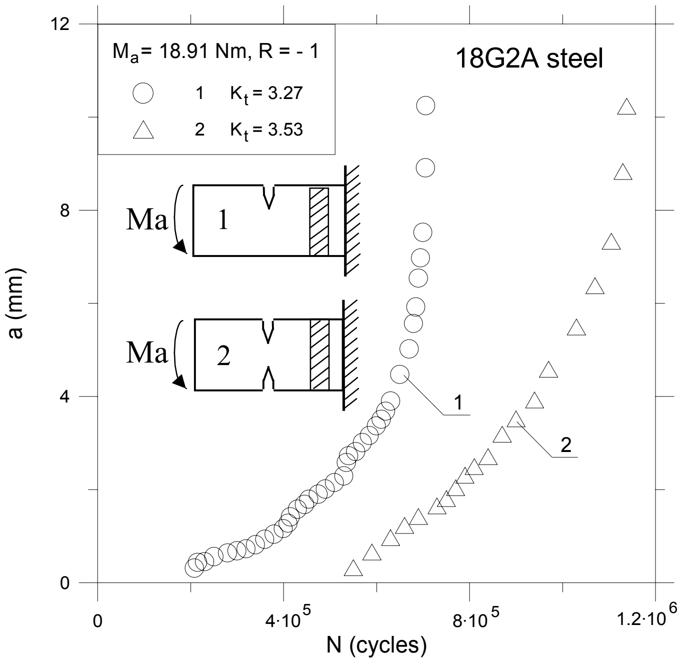

Figure 5. Fatigue crack growth versus a number of cycles for M_a = 18.91 Nm for various stress concentrators.

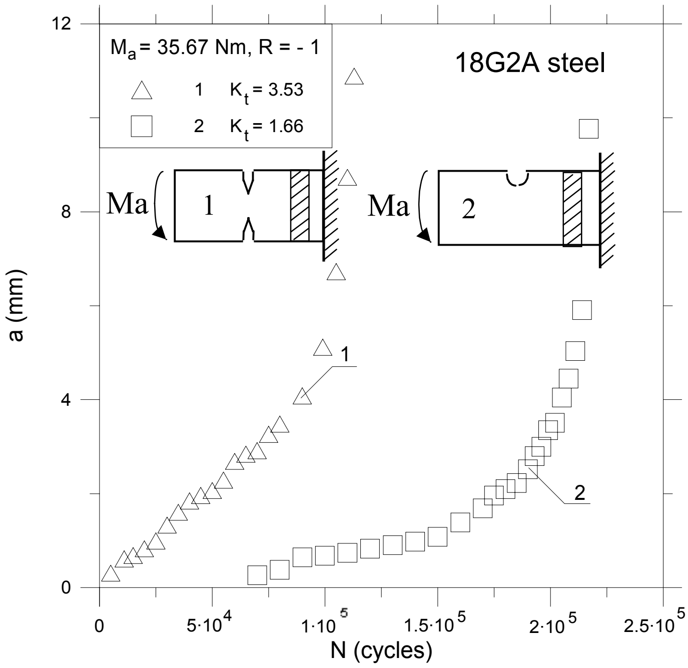

Figure 6. Fatigue crack growth versus a number of cycles for M_a = 35.67 Nm for various stress concentrators.

Figure 5 presents the crack length growth versus a number of cycles for M_a = 18.91 Nm for two specimens with various stress concentrators, one sided and two-sided sharp notches. It can be seen that under the assumed loading the life of the specimens with the sharp two-sided notch was also longer than the life of specimens with the sharp one-sided notch. Fig. 6 shows the graphs a = f (N) for M_a = 35.67 Nm and two specimens with the stress concentrators, two-sided sharp and one-sided blunt notches. From this figure it appears that a specimen with the one-sided blunt notch has significantly longer life than a specimen with the two-sided sharp notch.

CONCLUSIONS

From the performed tests of specimens made of 18G2A steel we can draw the following conclusions:

1. In one-sided restrained specimens with the rectangular section and one-sided or two-sided notches under symmetric plane bending, the fatigue crack path proceeds usually according to Mode I. A certain curvature of crack line from the straight line is observed in the case of one-sided blunt notches.
2. The fatigue life of specimens with the two-sided sharp notch appears to be considerably longer than the life of specimens with the one-sided notch.

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