Fatigue crack path and propagation rate at weld root in cruciform joint

A Y Shlepetinskiy 1,*, K P Manzhula 2 and A G Saveliev 3

1 Engineering Centre JSC «REP Holding», Saint Petersburg, Russia
2 Peter the Great St.Petersburg Polytechnic University, Russia, 195251, Saint Petersburg, Polytechnicheskaya, 29
3 Moscow Automobile and Road Construction State Technical University, 125319, Moscow, Leningradsky Prospect, 64.

* E-mail: A.Shlepetskiy@reph.ru

Abstract. The results of experimental research of the path and propagation rate of fatigue cracks in cruciform welded joint with a lack of fusion are presented. It is shown that the cracks are initiated at and propagates from the all non-fused weld root faces. Experimental results are compared with the data of computer simulation in Ansys, and with numerical calculations of fatigue life using the received equations of stress intensity factors at the weld root.

1. Introduction

In the construction of machines and structures with complex configurations, there are constructional-technological lacks of fusion. Constructional lack of fusion is often caused by the impossibility of welding the root of the weld due to the constraints of the geometric dimensions. Technological lack of fusion is usually the result of a violation of welding technology. Being stress concentrators, lack of fusion under cyclic loading causes fatigue cracks to appear. Welded joints with lack of fusion by the degree of danger of fatigue failure are assigned to the most dangerous classes FAT36 [1], K4 [2], W [3, 4], C [5]. In [6–8], it was shown that the weld root (tip lack of fusion) is characterized by different degrees of sharpness and therefore the feature of weld root can be considered as almost ready macrocrack or concentrator with radii at the tip.

In this paper, sharp crack-like lack of fusion is considered. To assess the fatigue life of a joint with sharp crack-like lack of fusion, it is necessary to know the stress intensity factors (SIF) at the tip, the crack path, the crack propagation rate, and the loading cycle parameters.

Numerical researches of SIF at the weld root were carried out in [8–12], in which the SIF dependences on the influence of the joint geometrical parameters and the crack size were received.
2. Experimental and numerical studies

In this work, the crack propagation path and rate from the weld root in a cruciform welded joint were determined experimentally. The geometrical dimensions of the studied samples are shown in Figure 1. The plates thickness were 40 mm. The sample thickness was 16 mm. To reduce the probability of fatigue cracks appearance at the weld toe, they were additionally mechanically processed with the radii shown in Figure 1.a. Macrophotography of the samples showed that the gap between the non-fused weld root faces was averages 0.4 mm.

![Image](image_url)

**Figure 1.** Experimental sample with dimensions –a); leading and secondary fatigue cracks in experimental sample – b)

The joint was made of rolled low alloy structural steel for welding construct steel 09G2S. The chemical composition and mechanical properties of rolled steel 09G2S are presented in tables 1 and 2.

**Table 1.** Chemical composition low alloy structural steel for welding construct steel 09G2S of experimental sample (%).

| C  | Si  | Mn  | S  | P   | Cr  | Ni  | Cu  | N   |
|----|-----|-----|----|-----|-----|-----|-----|-----|
| 0.1| 0.7 | 1.49| 0.008| 0.018| 0.04| 0.04| 0.08| 0.005|
Table 2. Mechanical properties low alloy structural steel for welding construct steel 09G2S of experimental sample.

| Steel grade and category | Tensile strength, MPa | Yield strength, MPa | Relative extension, % | Impact strength after mechanical aging, t=20, J/cm² | Impact strength KCU t=40, J/cm² |
|--------------------------|-----------------------|---------------------|-----------------------|---------------------------------------------------|---------------------------------|
| 09G2S-12                 | 510                   | 360                 | 30                    | 85                                                | 117                             |

Welding was carried out by a semiautomatic device in a protective gas environment (80% argon, 20% carbon dioxide) with welding wire 08G2S without welding the root in such a way that non-welded between base plate and attachment plates.

The tests were carried out on an INSTRON 8806 servohydraulic machine. A Dynacell model strain gauge force sensor is mounted on a fixed traverse, which, together with a switching and recording measurement system, is a force-measuring device of the system. The Dynacell sensor has a built-in accelerometer, which makes it possible to compensate for the error in force measurement resulting from the action of inertial forces of moving masses (grippers, devices, etc.).

The loading frequency in all experiments was the same and was 5 Hz, i.e. 18000 cycles took place in one hour of continuous loading. The loading cycle was a slightly shifted to the side of the tensile cycle (R=0). The minimum value of the load in the cycle was 1500 N. The parameters of the load, the frequency of loading, the restrictions on displacements and the number of cycles passed were controlled using a computer. The crack existence and position was determined in a visual way using a Brinell loupe. The crack tip position at a certain moment of the passed number of cycles was recorded by a mark, with an error of no more than 0.5 mm, and a microphotograph of the crack path was taken. Since the weld roots have insignificant roundings, a certain period of macrocrack formation was observed in the experiments. Researches have shown that fatigue cracks develop from all weld roots, but at different rates. There is always a leading crack, the formation period of which is the shortest and growing faster than the others, which can be called secondary (Figure 1, b).

The crack front, especially in the initial period, corresponds to \(\frac{1}{4}\) of the ellipse, which is associated with the formation of a crack from the free border of the sample and the possible slight eccentricity of the installation of the sample. Figure 2 shows the lines of the crack front propagation on the left side and the right side of the sample, corresponding to the marked number of loading cycles.

Figure 2. Marked the crack front on a destroyed sample No. 2 with a fixed number of loading cycles.

The position of the crack tip was determined visually using a Brinell magnifier. After a certain number of cycles, the tip of the crack was fixed with a mark with an error of no more than 0.5 mm and
the trajectory was photographed. On the basis of the obtained images, the crack length was determined by the graphical method.

In [8] the equation for SIF in the weld root in cruciform welded joint with axial longitudinal tensile load and using the method of forming the experiment plan [13] was obtained

\[
K_f = b_0 - 2.33(b_1 + b_2 + b_3) - 4b_3 - 1.67b_4 + 3.33b_1 \frac{K_g}{t_1} + 3.33b_2 \frac{a}{t_1} + 5b_3 \frac{K_g}{K_b} + 0.067b_4 t_2 + \\
+3.33b_2 \frac{t_1}{t_2} + b_2 \left(3.33 \frac{K_g}{t_1} - 2.33 \right) + b_4 \left(3.33 \frac{K_g}{t_1} - 2.33 \right) (0.067t_2 - 1.67) + \\
+ b_5 \left(3.33 \frac{K_g}{t_1} - 2.33 \right) + b_5 \left(3.33 \frac{a}{t_1} - 2.33 \right) (0.067t_2 - 1.67) + \\
+ b_{24} \left(3.33 \frac{t_1}{t_2} - 2.33 \right) + b_{25} (0.067t_2 - 1.67) + \\
+ b_{24} \left(3.33 \frac{K_g}{t_1} - 2.33 \right) + b_{25} \left(3.33 \frac{a}{t_1} - 2.33 \right) + \\
+ b_{25} \left(3.33 \frac{K_g}{t_1} - 2.33 \right) + b_{24} (0.067t_2 - 1.67) + \\
+ b_{25} \left(3.33 \frac{a}{t_1} - 2.33 \right) (0.067t_2 - 1.67) + \\
+ b_{24} \left(3.33 \frac{t_1}{t_2} - 2.33 \right) + b_{25} \left(3.33 \frac{t_1}{t_2} - 2.33 \right) + \\
+ b_{24} \left(3.33 \frac{a}{t_1} - 2.33 \right) (0.067t_2 - 1.67) + \\
+ b_{25} \left(3.33 \frac{t_1}{t_2} - 2.33 \right)
\]

(1)

The coefficients \(b_p\) are polynomials of the relative size of the crack increment and, in general, can be written as

\[
b_p = \beta_{0p} + \beta_{1p} \frac{a'}{w} + \beta_{2p} \left(\frac{a'}{w}\right)^2 + \beta_{3p} \left(\frac{a'}{w}\right)^3 + \beta_{4p} \left(\frac{a'}{w}\right)^4
\]

(2)

where \(\beta_{qp} (q=0,1,\ldots,4)\) is the coefficient before the corresponding degree of the multiplier \((a'/w)\), defined by table 3, \(p=0,1,2,3,4,5,12,\ldots,245\) - index indicating the corresponding parameter or group of parameters.

**Table 3.** The values of the equation (2) coefficients, obtained as a result of numerical experiment.

| \(\beta_0p\) | \(\beta_1p\) | \(\beta_2p\) | \(\beta_3p\) | \(\beta_4p\) |
|---|---|---|---|---|
| \(b_0\) | 10.89 | 11.06 | 54.03 | -136.15 | 155.96 |
| \(b_1\) | -2.56 | -0.04 | -9.67 | 17.76 | -25.59 |
| \(b_2\) | 3.40 | -0.98 | 8.15 | -15.28 | 18.22 |
| \(b_3\) | -0.33 | 1.79 | 6.76 | -24.03 | 37.66 |
| \(b_4\) | 3.62 | 4.91 | 8.22 | -21.15 | 34.29 |
| \(b_5\) | 2.69 | 1.89 | 25.74 | -64.90 | 56.18 |
| \(b_{12}\) | -1.37 | -1.46 | 2.91 | -6.26 | 1.97 |
| \(b_{14}\) | -0.86 | -0.12 | -3.90 | 8.41 | -12.95 |
| \(b_{15}\) | -0.63 | 1.27 | -14.28 | 38.71 | -31.89 |
| \(b_{24}\) | 1.13 | -0.26 | 1.36 | 0.61 | -2.91 |
| \(b_{25}\) | 0.67 | 0.59 | -3.28 | 7.70 | 0.32 |
| \(b_{45}\) | 0.90 | 2.05 | -4.90 | 15.58 | -14.66 |
| \(b_{124}\) | -0.45 | -1.41 | 7.71 | -19.44 | 16.34 |
| \(b_{125}\) | -0.31 | -0.18 | 0.01 | 0.05 | -5.75 |
| \(b_{245}\) | 0.516 | 0.628 | 3.246 | -8.634 | 9.554 |
The equation (1) gives more accurate results compared to equations [11,14]. When $K_b = K_g = K$ and $t_1 = t_2 = t$, the parameters like in experimental samples, the dependence (1) can be represented as

$$K_I = 1.87 + \frac{K}{l} \left( 1.254 - 10.077 \frac{a}{l} - 0.311a \right) + \frac{a}{l} (12.309 + 0.522t) + 0.079t + 0.031K +$$

$$+ \left( \frac{a}{w} \right) \left( -12.1 + \frac{K}{l} \left( 6.21 - 4.811 \frac{a}{l} - 0.636a \right) + \frac{a}{l} (10.877 + 0.271t) + 0.134t + 0.377K \right) +$$

$$+ \left( \frac{a}{w} \right)^2 \left( 48.073 + \frac{K}{l} \left( -13.556 - 3.833 \frac{a}{l} - 0.237a \right) + \frac{a}{l} (0.673 + 0.769t) + 0.607t - 0.37K \right)$$

(3)

In the finite element modeling (FEM) program Ansys, a crack growth was simulated [8]. In the crack tip surrounding, there were two layers of singular elements with a radius of the first layer of 0.01 mm. The root crack growth path was determined by the action of stress intensity factors $K_I$ and $K_{II}$, which were determined at each step of crack propagation, and the angle in the direction of which the crack will grow, from the condition of the normal to maximum normal tensile stress [15]. The values of the coefficient $K_{II}$ was less than 0.2 $K_I$ throughout the crack path.

According to the measurement results, trajectories and the dependence of the crack length on the number of loading cycles were described (Figure 3). The stress range of the tensile cycle was $\sigma=77$ MPa in sample 1, $\sigma=88$ MPa in sample 2, $\sigma=96$ MPa in sample 3.

![Figure 3](image-url)

**Figure 3.** The leading cracks propagation in the experimental samples - lines 1, 2, 3 (calculated points and approximate curves) and crack propagation by the FEM calculating at $\sigma = 70$ MPa, $C = 4.75 \cdot 10^{-12} \text{MPa} \cdot \text{m}^{0.5}$, $n = 3$ - line 4.

The number of cycles was calculated simply by integration using the trapezoid method

$$N_i = N_{i-1} + \frac{1}{0.5(v_i + v_{i-1})(K_i - K_{i-1})},$$

where $v$ is the crack propagation rate. The parameters of the Paris equation were $C=4.75 \cdot 10^{-12} \text{MPa} \cdot \text{m}^{0.5}$, $n=3$. In Figure 3 points 1 correspond to the...
experimentally obtained in sample 1, and the line to approximate curves. The curve 4 is calculated by the FEM.

In Figure 4 for sample 1 shows a comparison of the experimental real crack paths with the FEM calculated crack paths.

![Figure 4. Comparison the crack path in sample 1.](image)

The shift to the right along the number of cycles of the experimental points and curve 1 relatively to curve 4, obtained by FEM simulation, is explained by the fact that when calculating the FEM, a complete crack was considered, which reached a threshold value at the tip \( \Delta K_{\text{th}} = 9.3 \text{ MPa} \cdot \text{m}^{0.5} \) (for 09G2C, [16]). In the experimental samples, concentrators with radii were observed at the weld root, so there was an incubation period for a macrocrack formation.

3. Conclusion
The experimental research of cracks initiation and propagation from the weld root showed that fatigue cracks grow from all non-fused weld root faces. The fatigue cracks propagation rate is not the same, there is one crack that grows faster than the others. The FEM simulation of the crack path corresponds well enough to the experimentally observed trajectories of fatigue cracks from weld roots. Calculations of crack growth periods to critical sizes using the Paris equation and the dependences \( K_\text{I} \) on the geometry parameters of a welded cruciform joint obtained in the work agree well with the experimental results and can be used for practical applications. In this case, it is necessary to take into account the correction for the period of formation of a macrocrack at the lack of fusion tip.

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